



Exploration & Production

## GENERAL SPECIFICATION

### PIPELINES - RISERS

#### GS PLR 151

|                                              |
|----------------------------------------------|
| <b>Design of steel catenary riser system</b> |
|----------------------------------------------|

|      |       |                                                |
|------|-------|------------------------------------------------|
|      |       |                                                |
| 01   | 09/03 | General review – Change of Group name and logo |
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## 1. Scope

This document - which supplements the [GS PLR 100](#) - defines the minimum requirements for the structural detail design specific to carbon steel catenary riser systems operated from floating production systems (application on deep water field developments).

### Applicability

This specification is limited to the design of carbon steel catenary riser in sweet service conditions.

Pipe-in-pipe SCR, titanium, composite catenary risers or SCR with a piggy back system are not within the scope of this document.

### Important remark

The design and installation of steel catenary risers is still a developing technology and experience within the offshore industry is limited to a small number of installations on recent field developments.

Technical uncertainties remain regarding some aspects of the design process.

Physical basis underlying some key phenomena such as VIV, riser – soil interaction shall be carefully assessed.

Recommendations of this specification are therefore based on the last most reliable research findings and observations.

Continued development is undergoing to include the recognised shortcomings and to keep this specification updated.

### Basis

[DNV OS-F201](#) is used as the basis for this specification.

The intent of this specification is to provide statements of guidance relating to catenary risers to supplement the basic requirements of [DNV OS-F201](#).

In addition to the design issues covered in this specification, the overall philosophy to be adhered to during SCR construction, is to emphasis quality over speed so as to achieve production of very high quality welds.

### Overview of the document

The overall approach towards SCR analysis and design is outlined below.

- section 4 - Design philosophy: field of application of SCR technology and limit of applicability
- section 5 - Design data: data required to enable detail design of SCR
- section 6 - Design methodology: minimum requirements in terms of calculation, load cases, etc.
- section 7 - Design of ancillary SCR components: important remarks on SCR components non covered by the Design methodology section.
- Appendix Appendix 1 is providing a bibliography in relation with theoretical approach and technology of SCRs.
- Appendices Appendix 2 to 15 are providing outlines of calculation methods for the design of the SCRs

## 2. Reference documents

The reference documents listed below form an integral part of this General Specification. Unless otherwise stipulated, the applicable version of these documents, including relevant appendices and supplements, is the latest revision published at the EFFECTIVE DATE of the CONTRACT.

### Standards

| Reference   | Title                                                                            |
|-------------|----------------------------------------------------------------------------------|
| DNV OS-F201 | Offshore Standard - Dynamic Risers                                               |
| DNV OS-F101 | Offshore Standard Submarine Pipeline Systems                                     |
| ISO 9001    | Quality Management Systems – Requirements                                        |
| BS 7910     | Guide on methods for assessing the acceptability of flaws in metallic structures |

### Professional Documents

| Reference     | Title                                                                                    |
|---------------|------------------------------------------------------------------------------------------|
| DNV RP C203   | Fatigue Strength Analysis of Offshore Steel Structures                                   |
| API RP 2RD    | Design of Risers for Floating Production Systems (FPSs) and Tension-Leg Platforms (TLPs) |
| API RP 1111   | Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines       |
| API RP 2SK    | Design and Analysis of Station Keeping Systems for Floating Structures                   |
| API RP 2A-WSD | Planning, Designing and Constructing - Fixed Offshore Platforms - Working Stress Design  |
| API 5L        | Specification for Line Pipe                                                              |
| DNV CN 30.5   | Environmental Conditions and Environmental Loads                                         |

### Regulations

| Reference      | Title |
|----------------|-------|
| Not applicable |       |

### Codes

| Reference      | Title |
|----------------|-------|
| Not applicable |       |

## Other documents

| Reference  | Title                                                                                                                                                        |
|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|
| DoE<br>HSE | U.K. Department of Energy Guidance Notes 1990<br>Offshore Technology Report OTO2000-043 - Guidance for Fatigue Design and Assessment of Pipeline Girth Welds |

## Total General Specifications

| Reference  | Title                                                                   |
|------------|-------------------------------------------------------------------------|
| GS PLR 000 | General Specification Catalogue                                         |
| GS PLR 001 | Documentation Requirements                                              |
| GS PLR 002 | Organisation of the Design Works                                        |
| GS PLR 100 | Submarine Pipeline Systems                                              |
| GS PLR 201 | Fabrication of seamless pipes for pipelines (Sweet effluent)            |
| GS PLR 430 | Automated Ultrasonic Examination (AUT) of Pipeline Girth Welds          |
| GS SAF 021 | Lay-out                                                                 |
| GS SAF 261 | Pressure protection and relief emergency shut-down and depressurisation |

## 3. General

### 3.1 Definitions

For the purpose of this specification, the following are interpretations irrespective of any other meanings the words may have in other connections:

**WORK** means the design, engineering, procurement, installation, commissioning of the steel catenary riser.

**Project Specification** Project specific document defining the functional requirements for equipment and systems required for a field development project.

### 3.2 Nomenclature and abbreviations

|      |                                                                                     |
|------|-------------------------------------------------------------------------------------|
| Ca   | Added mass coefficient                                                              |
| Cd   | Drag coefficient                                                                    |
| Cf   | Design case factor (reference API 2RD)                                              |
| Cm   | Inertia coefficient                                                                 |
| D    | External Diameter, dimensional tolerance in <a href="#">DNV OS-F101</a> , section 6 |
| F    | Fracture arrest requirement in <a href="#">DNV OS-F101</a> , section 6              |
| FPS  | Floating Production Support                                                         |
| FPSO | Floating Production Storage Off Loading                                             |

|              |                                                                  |
|--------------|------------------------------------------------------------------|
| <b>L</b>     | Length                                                           |
| <b>LAT</b>   | Lowest Astronomical Tide                                         |
| <b>NDT</b>   | Non Destructive Testing                                          |
| <b>P-M</b>   | Pierson-Moskowitz                                                |
| <b>QA/QC</b> | Quality Assurance / Quality Control                              |
| <b>RAO</b>   | Response Amplitude Operator                                      |
| <b>Re</b>    | Reynolds number                                                  |
| <b>RMS</b>   | Root Mean Square                                                 |
| <b>ROV</b>   | Remotely Operated Vehicle                                        |
| <b>SCR</b>   | Steel Catenary Riser                                             |
| <b>SMYS</b>  | Specified Minimum Yield Strength                                 |
| <b>TDA</b>   | Touch Down Area                                                  |
| <b>TDP</b>   | Touch Down Point                                                 |
| <b>TLP</b>   | Tension Leg Platform                                             |
| <b>U</b>     | Specific requirement for pipe material in DNV OS-F101, section 6 |
| <b>VIV</b>   | Vortex Induced Vibration                                         |
| <b>WSD</b>   | Working Stress Design                                            |

## 4. Design philosophy

### 4.1 Design code

The basic design code is the [DNV OS-F201](#) with reference to [DNV OS-F101](#) for material, testing and installation issues.

Adequate supporting documentation and validation of computational methodology by physical testing shall be supplied, demonstrating adherence to [DNV OS-F201](#) and [DNV OS-F101](#) requirements.

### 4.2 Engineering capability

#### 4.2.1 CONTRACTOR selection

The CONTRACTOR proposed for the WORK shall satisfy the following:

- Its design team shall be made of experienced personnel familiar with the design, engineering, fabrication, installation and commissioning of marine riser systems. Key personnel shall have previous experience in the detailed design of SCRs.
- Its design team shall have a high performance support hot line for all the software used and must be competent in Finite Element Analysis (FEA).
- Its design team shall include the necessary experienced personnel in charge of interfacing with all others disciplines (flow assurance, installation, etc.) to ensure the design will fulfil all functional and operational requirements.

- A quality management system in compliance with [ISO 9001](#) or other equal quality management system, covering all aspects of the WORK shall be operated.
- The systems shall ensure that quality management of the WORK as a whole is applied from inception to completion.
- [GS PLR 002](#) requirements

## 4.2.2 Software selection

### 4.2.2.1 Global analysis software

SCRs analyses shall be performed with a 3-D finite element code dedicated to the analysis of marine riser systems.

The selected software shall have an independent certification based on analysis of general riser modelling.

CONTRACTOR shall provide model test comparisons for validation of specific items listed above.

The software shall have the capacity to:

- Enable static and dynamic (time domain) analyses, modal analysis and frequency analysis
- Allow 3-D formulation for translation, rotation and torsion
- Model slender structures and cope with large displacements
- Model hydrodynamic forces and FPS motions (Low Frequency motions, RAOs)
- Model non-linearity's (material properties, flexible joint characteristics, riser – soil interaction, etc.)
- Model elastic seabed contact with anisotropy friction law and slope (coherent with non linear soil behaviour)
- Predict in-plane and out-of-plane buckling of the pipe.
- Take into account bending – torsion coupling effect
- Take into account interference between risers
- Enable mooring – riser coupling analysis
- Model thermal, pressure and slugging loading
- Model adequate structural damping formulation
- Model sudden vertical displacement leading to a peak bending stress travelling along the riser, caused by mooring failure for instance (ref. Stride Phase 3 – 1300RPT009)

With regard to post-processing, the following items shall be direct standard outputs:

- Global riser position (distance to other structure, deviation angles, curvature)
- Cross-sectional forces (effective tension, bending moments, torsional moment)
- Stresses (principal stresses and combined)
- Forces at riser connection to rigid structure
- Fatigue life assessment

- [DNV OS-F101](#) and [DNV OS-F201](#) codes unity checks for local buckling (combined loading criteria) at each node along the riser length.

#### 4.2.2.2 Vortex induced vibration analysis software

Vortex Induced Vibration analysis shall be computed based on multi-modal response analysis, wake oscillators or resolution of Navier-Stokes equations. Partial resolution of RANS equation i.e. using strip theory and assuming 2D flow in transverse direction, may be acceptable providing software validation is produced to COMPANY satisfaction.

Selected software shall be validated or calibrated against a set of small and full scale tests representative of the currents characteristics analysed.

Efficiency of anti-VIV devices shall be supported by CFD calculation, small or full scale tests.

The software shall, as a minimum, have the capacity to:

- Take into account current direction, speed and their variation with depth
- Take into account realistic Reynolds numbers (and associated turbulence modelling)
- Take into account riser displacement inducing VIV
- Take into account anti-VIV devices with their location, shape and efficiency

The following outputs shall be calculated by the selected software:

- Modified drag coefficient
- Fatigue damage calculation
- Vibration amplitude of the riser response
- Curvature and bending stress along the riser curvilinear length
- Definition of the excited modes (lock in zone) along the riser curvilinear length
- Identification of the most energetic mode as well as the most damaging one
- Detail of the energy level associated to each excited mode
- Fluid velocity
- Strouhal number

### 4.3 General layout configuration

The general configuration of the site layout including SCRs shall take into account the following considerations:

- The SCR shall not contribute to the mooring of the floating unit.
- Clashing of the SCRs with adjacent risers, umbilicals, mooring lines or the FPS is not permitted neither during installation nor operation.
- Layout shall allow for SCR disconnection (see section 4.13). Requirement for SCR pre-installation may also be considered and shall be specified in Project Specification if applicable.
- Layout shall allow for future riser installation on the FPS.
- Crane operations should be prohibited above sealines and risers unless they are suitably protected against maximum load impact.

- Consequence assessment using dropped cone type analyses may be required to ensure dropped loads cannot damage the pipeline and riser system.
- Where the potential of damage from dropped loads cannot be completely eliminated, a derogation from **GS SAF 021** shall be required.
- This shall include justification that the possibility of damage is sufficiently reduced and that suitable measures have been put in place in the event of damage occurring.
- Impact protection shall also be considered in the safety analysis of the general lay out
- First assessment of the minimum clearance between SCRs shall be conducted considering that no wake effect is present i.e. for risers analysed in pairs assumption that one riser is not affected by current shall be made. However, if clashing does occur, a less conservative approach considering “partial” wake effect can be used providing methodology is approved by COMPANY.
- SCR layout shall optimise the riser attachment location on the FPS and flaring angle so as to minimise motion effects. However, due consideration for installation safety shall be accounted for.
- The length of riser on the seabed shall be sufficient to prevent dynamic tension or bending being transmitted to the attached flowline or other subsea equipment.
- Adverse installation tolerances of the host FPS and the interface with the attached subsea flowline / pipeline shall be included in the analyses.
- SCR installation tolerances, such as but not limited to, TDP target box and flaring angle, shall be accounted for in the design.
- Variations in water depth and host FPS draft in conjunction with the defined FPS excursions due to operational and accidental load conditions shall be allowed for.
- The effect of pipeline and riser expansion combined with SCR bottom tension and seabed slope, shall be considered in the riser “in-place” study; this may require straight length of pipeline close to TDP followed by large bending radius and anchoring of the pipeline if the static section is short with a soil with low friction characteristics. The system shall provide adequate resistance to prevent slippage of the SCR TDP.
- The evolution of the TDA (long term, including trenching and natural backfilling) shall be taken into account.
- Preference shall be given to a Full Pressure Rated Design i.e. capable of withstanding the worst foreseeable normal or abnormal process conditions. Thereafter, active protection systems shall be applied as per **GS SAF 261**.
- Location shall be selected to minimise potential for escalation of riser events (fires/explosions/unignited gas) to other safety critical areas such as adjacent risers, other flammable inventories, accommodation, emergency response facilities and systems maintaining FPS station or integrity.
- Conversely, the vulnerability of the SCR from other fire and explosion events such as sea pool fires or topsides explosions shall also be a fundamental consideration when selecting the riser location. Design reviews shall thoroughly address the Safety issues during this phase of the FPS layout and SCR design process.
- Need for SSIV shall be evaluated to reduce pipeline inventory ; if deemed necessary SSIV shall be included in the layout (on the sea bed or at pontoon level)

#### 4.4 FPS interface

The top of the SCR shall be connected to the host FPS structure in a location which minimises the exposure to hazard and the effect of FPS dynamics on the riser.

The preferred location depends on the type of facility, installation modes, inspection philosophy, etc.

In all cases, the hang-off shall be close to the centre of pitch / roll and shall be designed to resist torque in the riser arising from reel installation of the riser, accumulated changes in flowline direction and FPS offset and yaw motions.

#### 4.5 Corrosion

There is at present insufficient confidence relating to corrosion fatigue aspects to specify SCR for sour service: SCRs shall be used for sweet applications.

External corrosion protection of SCR shall be achieved using a combination of corrosion resistant coatings and sacrificial anodes. Additional coating protection shall be considered in the TDA.

The design of the corrosion protection system shall be compatible with the cathodic protection systems fitted to the host FPS and to any subsea equipment close to the riser.

Particular attention shall be paid to the system voltages and current density where use is made of dissimilar materials e.g. titanium or material which may be prone to hydrogen embrittlement, e.g. super duplex.

For application where corrosion is foreseen, the use of internal cladding at TDA and at high stress zone shall be investigated.

#### 4.6 Anti-fouling recommendation

Anti-fouling coatings shall be applied on the SCR to inhibit marine growth.

Any marine growth appearing shall be removed periodically in order to ensure the efficiency of the VIV suppression device.

Despite the above, the design shall allow for a reasonable level of marine growth.

#### 4.7 Material selection

High quality line pipe is required for SCR application and in order to ensure a uniformly consistent level of integrity in design and manufacture the line pipe shall meet the requirements of [DNV OS-F101](#), section 6.

Material selection shall cover the detailed assessment of :

- strength requirements
- adequate material toughness for fracture and fatigue performance
- weld defect acceptance criteria
- corrosive environment requirements.

In addition, the following considerations shall be adopted:

- Supplementary requirements identified in [DNV OS-F101](#) (fracture arrest (F) and dimensions (D)) shall apply.

- Grade above X65 are not qualified for SCR's.
- Threaded connection are not qualified for SCR's.
- SCR application shall be limited to seamless pipe.
- Machining or matching of the pipe ends is recommended in order to avoid geometrical discontinuity between each pipe joint.
- For the sections subject to large bending (TDA, top of riser), selection of pipe joint with similar strength properties and stiffness is recommended.

Temperature de-rating of material properties shall satisfy [DNV OS-F201](#) -section 5 – C303 requirements.

## 4.8 Welding

A dedicated General Specification will be generated at the next revision of the COMPANY General Specifications to cover the Welding Issues of the SCRs.

However, the following minimum requirements shall be satisfied:

- Repairs to SCRs welds are not allowed.
- A hi-lo of 0.5mm shall be achieved in the SCR critical welds area (typically in the TDA and at the top of the SCR – but these areas have to be defined by the detailed fatigue analysis).
- Only automatic welding process are allowed.
- Engineering Critical Assessment (ECA) shall be carried out according to Level 2 of [BS 7910](#) taking into account plastic-collapse and brittle fracture modes of failure as detailed in Appendix Appendix 5. In any cases, the final SCR acceptance criteria shall be approved by COMPANY before implementation. This criteria shall be within the values tabulated in Appendix 5 where typical data gained from past experience are outlined.
- Welding Procedure Qualification shall satisfy the requirements defined in the Project Specification. In addition, tensile specimens tested during the welding procedure qualifications must fail in the pipe body and not in the weld area. This overall qualification process shall culminate with the performance of full scale fatigue testing. These tests shall satisfy the requirements defined in the Project Specification.

## 4.9 Through riser operations

### 4.9.1 Pigging

The overall design of the SCR shall take into account the requirement to pig the riser and associated pipeline both during commissioning and as a routine part of operations.

In particular, flexible joints shall be specified to permit pigging operations and the limiting values of FPS offset shall be established corresponding to the maximum angular displacements of the flexible joints for satisfactory pigging operations.

### 4.9.2 Well service, coil tubing

Unless the SCR is specifically designed for it, it is not permitted to carry out well service operations through SCRs, or coil tubing interaction.

#### 4.10 Flow assurance

Detailed studies should be performed as part of the SCR design process to establish the required line diameters, thermal insulation requirements and the size, frequency and velocity of slugs appearing in the risers.

Slugging shall be examined in sufficient detail to identify any requirement for a separate design load case.

#### 4.11 Installation considerations

CONTRACTOR shall ensure that the installation operations will not induce temporary or permanent strain in the pipe wall that could affect the integrity of the SCR over its full service life.

Installation by reeling is accepted provided that a project's specific detailed study of the reeling effects has demonstrated that the reeling operation does not adversely affect the integrity of the SCR. In particular, the high strains involved in reeling and straightening of the pipes can give rise to simultaneous ductile tearing and low-cycle fatigue crack growth (so-called tear fatigue) that can cause pre-existing weld flaws to extend, thereby potentially reducing the life of reeled risers compared to conventionally installed risers with the same fabrication flaws. As a result, simultaneous ductile tearing and tear fatigue shall be quantified based on a combination of analytical formulations, small scale testing and full scale testing.

In addition, the study shall include tests using samples of the riser pipe to establish limits on residual ovality, residual strain and on full scale welds to establish any effect on fatigue life.

Installation method shall enable suspension and reversal of the procedure.

General configuration shall be selected such as the installation can be performed with standard equipment (maximum capacity of about 500T without any safety factor).

#### 4.12 Pressure test

The riser system shall be pressure tested in place following installation but before being put into operation.

Pressure testing shall be carried out to demonstrate the integrity of the completed riser system. Test pressures, hold time and acceptance criteria shall not be less onerous than required by [DNV OS-F101](#) Section 5 B 200.

If the riser appurtenances are all hydrotested prior to installation then the pressure test performed on the riser system might be conducted as a combined strength and leak test.

#### 4.13 Riser disconnection

SCRs shall be designed to be safely disconnected and recovered or temporary wet stored (laid on the seabed, etc) in the event that the host facility is required to leave site as per planned schedule.

Provision shall be made on the host facility for the temporary equipment and facilities required for this operation.

Transfer of the riser from the host FPS and lay down on the seabed shall be engineered with extreme care taking into account the different load cases applying to installation (e.g., flooded riser, dynamics of lift FPS, effects of off-design configuration).

Equipment should be specified based on the results of simulation analysis of disconnection operations and should include substantial margins to account for the critical and non-standard nature of these operations.

## 4.14 Inspection, maintenance and repair

### 4.14.1 Inspection

As a minimum, the design of SCR shall accommodate the following routine inspection operations:

- External visual and cp potential surveys carried out on an annual basis using ROVs.
- Intelligent pigging.
- Riser support on the FPS (flexible joint or stress joint) inspection for wear or damage.

### 4.14.2 Maintenance and repair

The risers system shall be designed for operation throughout the life of the installation without any scheduled maintenance or repair.

In-situ repair of structural damage to catenary risers is not considered feasible.

It is therefore recommended that project considers sufficient redundancy / flexibility in the riser system (use of dual production riser, interconnectability...).

The layout of the field and riser facilities shall facilitate the removal of a damaged SCR and the installation of a replacement (without any clash with other existing facilities).

## 4.15 Riser monitoring

Each riser system including SCRs shall be fitted with a riser monitoring equipment.

The minimum requirement will be to obtain a measure of the consumption of fatigue life of, at least, one of the SCRs. This can be achieved by calibration of the fatigue life consumption assessment based on riser monitoring at early stage of the field development.

The monitoring system shall require analytical calibration to correlate between the results obtained at the locations of the monitoring equipment and the rest of the riser.

The monitoring equipment shall be located to respond to both wave action and to VIV.

Measurement of the associated vessel motion shall be conducted.

## 5. Design data

The purpose of this section is to define the information required to design an SCR. The following information shall be gathered before starting SCR engineering.

### 5.1 Riser data

The minimum riser data required for conducting riser design are:

- Line size
- Top angle
- Material properties

- Coatings characteristics
- Hydrodynamic properties
- Pipe external roughness
- Presence of anode
- Shielding / enhancement from adjacent risers and structures

## 5.2 Fluids data

### 5.2.1 Internal fluid

The minimum internal fluids data required for conducting riser design are:

- Internal pressure (incidental, operating)
- Density (max, min, average)
- Temperature (max, min)
- Chemical composition of effluent and chemical (used for service, drilling...)

### 5.2.2 External fluid

- Temperature
- Density
- Presence of H<sub>2</sub>S, etc.

## 5.3 Meteocean data

Due to the high sensitivity to hydrodynamic loads, it is essential that site specific meteocean data shall be available for the design of SCR systems.

Where there are specific events such as summer storms, winter storms, loop currents or tropical storms / hurricanes, the data relating to these conditions should be grouped in a way that the designer can address each of these meteocean events as a specific design case.

The minimum meteocean data required for conducting riser design are:

- Local wave / swell data (simultaneous crossed seas)
- Current data (profile and scatter diagram)
- Marine growth

A detailed description of the meteocean data required is given in appendix 9 of this document.

Local waves shall be investigated: meteocean data sometimes do not allow for the wave category since they are less important than swell. However local sea can have an impact on fatigue.

## 5.4 Geotechnical and geophysical data

### 5.4.1 Geotechnical data

The geotechnical data shall be specific to the development site and representative of the conditions that will be encountered by the riser in service.

Details of soil chemistry and composition should also be obtained for the purpose of adequately specifying the pipe coating, corrosion protection and anti-abrasion coatings.

The soils at or close to the seabed in deep water are generally very soft to soft clays, although the presence of sand layers cannot be discounted.

Normally only the upper 5 meters of the seabed are of interest for SCR analysis.

The soil properties required for SCR modelling are different for clays and sands, and are given in the sections below.

For SCR analysis the main riser – soil interaction effects to model are summarised below:

- Downward vertical soil reaction – indentation into the soil, including static soil stiffness and dynamic cyclic loading
- Upward vertical soil reaction – resistance to uplift of the riser from the seabed including soil suction, static soil stiffness and dynamic cyclic loading
- Longitudinal and transverse soil reaction including frictional forces and passive resistance to lateral motion
- Viscous effects of soil damping

#### 5.4.1.1 Clay

The clay soil parameters required for SCR analysis are given in table below:

- Undisturbed shear strength
- Shear strength gradient with depth
- Sensitivity of clay
- Submerged unit weight
- Poisson's ratio
- Void ratio
- Plasticity index
- Lateral friction coefficient
- Axial friction coefficient

Typical values are given in Appendix 3.

#### 5.4.1.2 Sand

The sand parameters required for SCR analysis are given in table below:

- Submerged unit weight
- Angle of friction
- Poisson's ratio
- Voids ratio
- Lateral friction coefficient
- Axial friction coefficient

Typical values are given in Appendix 3.

### 5.4.2 Geophysical data

Sea bottom profile as well as the presence of any geo hazards (such as shallow gas, hydrates, etc.) shall be identified in the TDA.

## 5.5 FPS motion characteristics

### 5.5.1 General

Accurate characterisation of host FPS motions is critically important in developing reliable designs of riser system.

The key FPS motion data required for riser analysis is as follows:

- Static offset – the displacement resulting from mean environmental loads acting on the FPS i.e. wind, wave, current, often referred to as FPS mean position
- Wave frequency motions – the first order dynamic motions resulting from wave action and normally described by Response Amplitude Operators (RAOs)
- Low frequency motions resulting from second order wave forces and wind gust, often referred to as slow drift motions
- Other motions: VIV on FPS, springing ringing effect, etc.

Tests in basin shall be performed in order to validate numerical calculation of floating production unit RAOs and low frequency motions with risers in-place.

### 5.5.2 Mean position

The FPS mean position shall be determined from a mooring analysis based on environmental conditions which are consistent with the key riser design load cases.

This analysis shall consider normal operational conditions, failure / accidental loading cases and specific offset conditions associated with non standard operations (e.g. installation operations or offset to allow access to seabed equipment).

The effect of tension and drag from the risers shall be taken into account in the mooring analysis for the purposes of assessing FPS excursions and motions.

However, no account is to be taken of the risers when assessing the integrity of the mooring system or checking compliance with mooring system design codes.

### 5.5.3 Low frequency motions

Low frequency FPS motions data resulting from second order wave effects (long-term drift data) and wind gust loading is used in detailed SCR fatigue analysis where it is combined with FPS mean offset data.

These data should be determined from a mooring analysis conducted specifically for the mooring configuration intended for the host FPS and combined with the FPS mean position as described in [API RP 2SK](#) to provide the long term FPS motion data.

Influence of risers on wave drift damping shall be investigate and take into account if necessary.

### 5.5.4 Response Amplitude Operators (RAO)

FPS RAO data shall be provided describing the relationship between wave and corresponding FPS motion characteristics in six degrees of freedom.

They are often a key point in the riser system design and fatigue analysis; therefore, the derivation of these data shall be clearly documented on the following points:

- Values and method used to take into account the required damping for the waves frequencies motions, specially for ROLL, PITCH and HEAVE motions
- Values of the global stiffness used for the RAOs if a no free floating analysis is performed
- Riser / mooring stiffness, influence on the wave frequency motion should be highlighted if necessary
- Riser and mooring participation on the low frequencies damping
- Damping and  $H_s$  values considered for roll motion (maximum 1 meter)

They also shall be accompanied by the following information for correct conversion into formats suitable for the analysis software:

- Definition of FPS co-ordinate reference system and axis orientation
- COG location or RAO's reduced point shall be provided
- Associated FPSO condition: ballasted or fully loaded or mid laden (internal and external compartments)
- Definition of FPS direction relative to wave
- Definition of wave conventions (sine or cosine)
- Definition of phase angle relative to wave crest and platform origin (ie positive phase denoting lag or lead)

For preliminary design studies, the use of generic data may be adequate; however, for detailed design analysis, the RAO data shall, as a minimum be derived from a diffraction analysis of the specific hull form intended for the host FPS.

Where available, the use of model basin test data should be considered however, the data used should be representative of the sea states required for riser design analysis.

### 5.5.5 FPS loading configurations

The above information shall be given for different load conditions:

- ballasted
- full
- mid laden (external and internal compartment)

### 5.5.6 Other motions

Other FPS related effects having a significant influence on the design of SCR systems (such as SPAR VIV, TLP springing and ringing) shall be identified and taken into account if necessary.

CONTRACTOR shall investigate all other motions of the FPS which could impact on the SCR design:

- VIV on the hull of FPS
- springing effect (on TLP)
- DP
- etc.

## 5.6 Ancillary components data

The minimum required data for the flexible joint are:

- Axial and torsional stiffness as a function of the flexible joint angle
- Max and mean angle
- Temperature and pressure (operating and incidental)

## 5.7 Operational data

The minimum operational required data are:

- Slugging characterisation
- Shut down / start up number of cycles per year
- Risk of deposition (debris, wax, etc.)
- Pressure variation cycles

# 6. Design methodology

## 6.1 Acceptance criteria

The in-service design cases / load combinations are defined in the table below.

Each of these design cases shall be conducted for sufficient environmental loading directions to prove the design.

Typical limiting design criteria are given in the table below:

| Design criteria                                                    | Acceptance value                                                                    |
|--------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Stress in normal operating, etc.                                   | Refer to <a href="#">DNV OS-F201</a> – Section 5                                    |
| Fatigue due to combined load (WF, LF, VIV, etc.)                   | 10 times design life                                                                |
| Fatigue due to VIV                                                 | 20 times design life                                                                |
| Clearance from the FPS, mooring lines, umbilicals and other risers | No clashing (probability of occurrence < 10 <sup>-4</sup> per design life)          |
| Limiting flexible joint rotations                                  | 90 % of maximum flexion characteristics, based on tested components                 |
| Maximum interface loads                                            | As per structural design code ( <a href="#">API RP 2A - WSD</a> , if not specified) |
| Possible compression in the TDA                                    | Effective tension > 0                                                               |
| Tension on flowlines                                               | No residual tension on subsea component connected to SCR                            |

## 6.2 Design load case combinations

### 6.2.1 Accidental design load cases

Failed mooring with a 100 year wave condition is an accidental design case typically used in SCR design. One failed mooring line is not the only potential failure mechanism that will have an effect on the riser integrity. Other accidental design cases applicable to SCRs are listed as follows:

- Two or more failed mooring lines (or tethers on a TLP) – The location of the failed mooring lines for the analysis shall be selected so as to result in the most onerous condition in terms of SCR damage.
- Damaged hull compartments

The probability of each combination of environmental event with an accidental design case may be established by means of quantitative risk assessment.

For example, two failed mooring lines combined with a 100 year wave condition may have a low probability of occurrence.

In these situations an increase in the allowable stress, or a less severe environmental condition may be considered.

All design loads shall be considered as per [DNV OS-F201](#) – Section 3.

### 6.2.2 Internal fluids

For strength analysis, loading due to the internal fluid shall be included in terms of hydrostatic pressure and mass contribution to the riser system.

Fluids shall be considered static or in the steady flow regime (constant velocity).

The range of densities to be used in the analysis shall be chosen such as to cover all aspects of the riser installation and operation.

The effect of the axial elongation shall be investigated.

For fatigue analysis, the phenomenon of slugging shall be examined separately and the effect on the riser assessed as part of the detailed design.

### 6.2.3 Other loads

- Typically other loads are expansion of the riser, expansion of the line.
- The FPS shall be considered in its worst loading condition (which is normally the empty case).
- Temporary installation loads shall be included in the design.
- Functional loads induced by operation such as emergency shut down or fluids slugging or line pigging.

## 6.3 Safety class

Safety class classification shall satisfy [DNV OS-F201](#) – section 2 requirements.

In addition, for risers installed in array, due account of the geometric configuration and its inherent constraint shall be made for the definition of the safety class.

## 6.4 Wall thickness sizing analysis

### 6.4.1 Pressure containment criteria

The design of the riser pipe to resist internal pressure shall be in accordance with the methods and criteria of [DNV OS-F201](#).

The design shall take account of design pressure, maximum operating pressure and accidental overpressure and shall take correct account of relevant external pressures.

Unless directed otherwise by the project specification, the design pressure for the riser shall take account of the maximum pressure likely to be seen in the riser during its full life (emergency shut down included).

Care shall be given in the definition of the incidental pressure and subsequent design pressure so as to ensure consistency between the DNV pressure definition and the FPSO topsides design code definition.

### 6.4.2 Collapse criteria

Collapse criteria shall be used to ensure adequate wall thickness for the maximum water depth to be encountered.

Collapse design of catenary risers shall follow the requirements of [DNV OS-F201](#) – Section 5 D300 in the assessment of resistance to external pressure.

The combined resistance to external pressure, bending and tension shall satisfy the [DNV OS-F201](#) – Section 5 D500 requirements

The initial ovality of the riser sections shall not be taken less than the minimum value indicated by [DNV OS-F101](#). Ovalisation introduced during the construction phase shall be included in the ovality.

### 6.4.3 Buckle propagation criteria

The wall thickness determination of the SCR shall not be based on buckle propagation criteria. If buckle propagation is found to be critical for the riser, then buckle arrestors shall be used.

As a minimum, one buckle arrestor shall be included at the SCR / flowline interface to protect the sealine against any risk of buckle propagation during installation of the riser (lay away installation). Conversely the buckle arrestor located in the flowline, beyond the TDA will prevent a buckle propagating from the flowline to the riser.

### 6.4.4 Wall thickness sizing empirical assessment

Based on existing design it is recommended to have for SCR design a D/t ratio between 10 to 20 (dynamic consideration based on fatigue extreme results).

## 6.5 Finite element analysis

### 6.5.1 General

Riser global analysis shall be based on industry standard principles of finite element methods for static and dynamic studies.

The global model shall include the complete riser system with representative characterisation of system mass, stiffness, damping, top and bottom boundary conditions and hydrodynamic loads on the riser.

The floating unit complete with its mooring lines shall also be part of the global model.

## 6.5.2 Wave characterisation

### 6.5.2.1 Generalities

Riser response is period sensitive and analysing the maximum wave case with associated wave period may not result in the maximum response of the riser.

For this reason, the design analysis shall include a range of wave periods based on the range of possible steepnesses associated with the extreme wave height.

Furthermore, when specifying the wave periods to be included in the design analysis, reference to the host FPS RAO data shall be made to ensure that important peaks in FPS response are not overlooked.

References to the natural frequencies in the riser system shall also be made to ensure that significant peaks in the riser response are not overlooked.

### 6.5.2.2 Regular / irregular wave modelisation

- Regular wave analyses may be performed for strength analysis providing:
  1. The runtime is sufficient to get a stabilised response (generally not less than 4 periods).
  2. Conservatism of this method is checked against irregular wave analyses.
- Analysis runtime for irregular wave method shall not be less than 3 hours for determination of extreme responses and statistical checks shall be carried out to verify that the solution has converged to an acceptable level and that the design extreme event has occurred in the analysis.
- For time domain analyses considering wave and low frequency motions, the duration of the analysis must be considerably longer and statistical checks shall be carried out to confirm that the analysis has included extremes of both wave and low frequency motions.

### 6.5.2.3 Binning

The scatter diagram shall be organised into a sufficient number of representative bins. Typically, each bin shall not generate more than 20% of the total damage.

## 6.5.3 Hydrodynamic coefficients

CONTRACTOR shall document hydrodynamic coefficients used through the global analyses. The following points shall be taken into account:

- Flow regime (defined by Reynolds and Keulegan-Carpenter numbers)
- VIV occurrence and calculated increased drag (CFD may be used to calculate increased drag)
- Pipe roughness
- Presence of anodes
- Selection of the drag coefficient shall tend towards the conservative side: a higher value shall be used when and where drag acts as an excitation and a lower value when and where it acts to produce damping. Care must be taken to ensure that the selected hydrodynamic coefficients do not overly dampen the riser response.

- For SCRs organised in array, specificity of SCRs behaviours associated to this configuration as for e.g. reduction in the drag coefficient of the down stream riser shall be captured and accounted for.

Typical values for hydrodynamics coefficient are given in Appendix 4.

#### 6.5.4 Boundary conditions

SCR boundary conditions are the connection to the FPS and the interaction with the seabed. Care shall be taken to ensure that both are modelled to account for any non-linearities.

##### 6.5.4.1 Riser – FPS connection

The riser – FPS connection may comprise a flexible joint or a stress joint.

Flexible joints can be modelled as articulation elements (a pin connection with rotational stiffness), and the designer shall be aware of the sensitivities of flexible joint stiffness to both temperature and dynamic loading.

Taper stress joints may be modelled as a series of stepped sections. Due regard to convergence and accuracy of the analysis must be paid in considering element refinement in the stepped sections.

The orientation of the FPS attachment can have a big effect on end loading and termination sizing and shall be optimised.

##### 6.5.4.2 Riser – seabed interaction

Pipe – seabed interaction shall be modelled using either a rigid surface (which is considered conservative), a compliant surface or linear / non-linear springs and dampers.

These are combined with the effects of:

- Trenching and backfilling
- Load history, including consolidation time and load

The detailed design analysis of the riser in the seabed touchdown area shall address the range of soil properties represented by the upper and lower bounds in the data in order that a safe and robust design is developed. The fundamental soil parameters to be considered for accurate soil modelling are detailed in Appendix 6.

Simplified soil modelling may be acceptable provided that:

- Soil parameters are calibrated against test and soil mechanics formulation. Ideally, full scales tests shall be performed on soil sample collected on site. Otherwise, the property of the soil and the pertinence of the experiment shall be detailed and justified.
- A wide range of sensitivity analysis on each parameter is performed in order to assess soil characteristics unknown or modifications with time (trenching effect, consolidation...)
- Amplification factor on bending stresses at touchdown point due to suction effect is considered. A minimum value of 1.25 shall be used (Ref. Report 1300 – RPT009).

The potential for trenching effect and natural backfilling shall be investigated at riser bottom (TDA).

- Analyses of risers and pipelines use pipe – soil interaction models, which can be described in terms of linear or non-linear load – displacement curves.

Each translational degree of freedom, x, y, and z, has its own load – displacement curve as follows:

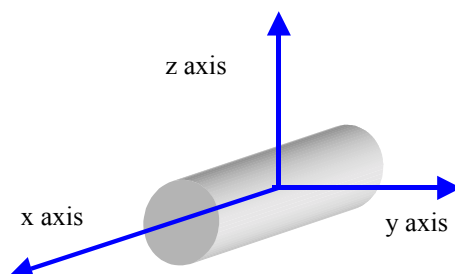


Figure 1 - local axes wrt pipe section

The vertical (z axis) is based on bearing capacity, cyclic loading or mixed formulations as described below:

- Bearing capacity: coefficient shall be validated against experiments as classical theory may not be appropriate for very superficial embedments and very soft soils (as it is the case in the TDA).
- Cyclic loading formulation: the averaged vertical stiffness shall depend on the cycle amplitude (as the main parameter). Ideally, the local amplitude of the cycles (and therefore the associated stiffness and damping of the soil-pipe interaction modelling) shall vary along the riser in the TDA.
- Mixed formulations involve successively monotonic loading, cyclic loading, and discharge phases down to suction.

The horizontal (y-axis) is a combination of friction and passive soil resistance.

The Axial (x-axis) is friction only.

Lateral pipe – soil interaction shall be considered for conditions where the FPS is pulled laterally, causing the riser to move into and possibly through the trench wall. Sensitivity analysis shall be conducted to determine the effect on fatigue damage and extreme stress.

Soil suction shall be considered for SCR installation and recovery analysis. Sensitivity analysis shall be conducted on riser fatigue damage.

## 6.5.5 Frequency domain / time domain

### 6.5.5.1 Time domain

In general, it is expected that time domain methods will be used for the assessment of extreme responses, and in order to calibrate frequency domain in the fatigue analysis.

### 6.5.5.2 Frequency domain

Linear frequency domain analysis should be based on a static equilibrium configuration derived from non-linear static analysis.

Frequency domain analyses shall be checked against time domain analyses to confirm that non-linearity in the model, loading and response are approximated with adequate levels of accuracy.

### 6.5.6 Mesh characterisation

When modelling SCRs, the element mesh shall be refined at locations of high curvature and dynamic response, typically directly below the interface with the FPS and in the TDA.

Both spatial and temporal discretizations shall be refined. The mesh size shall be compatible with the physical assumption underlying the numerical computation (e.g. slender structure assumption, Bernoulli or Midlin theory...). Convergence studies shall be conducted to ensure that a proper element discretization has been selected for the analyses (i.e. for VIV analysis and for the wave induced fatigue analysis).

Convergence criteria shall also be detailed and validated when dealing with seabed contact-friction interactions since the loads may vary over several orders of magnitude.

### 6.5.7 Floating production support modelling

Imposed displacement at the riser top is one of the key criteria of SCRs design.

The floating unit motions and riser / floating support interface shall be accurately modelled to ensure that representative reaction loads can be obtained at riser connection point.

As first approach, for fatigue analysis, mean position shall be the same for all directions and all (Hs, Tp) sea states.

Similarly, the condition of loading for the FPS (ballasted – full – mid laden) shall be the most conservative and for fatigue, 100% of the time in mid-draft configuration shall be used unless detailed assessment of the FPS loading condition and associated occurrence percentage is conducted at detailed engineering phase.

### 6.5.8 Damping

CONTRACTOR shall not use structural damping.

CONTRACTOR shall not use VIV damping due to soil.

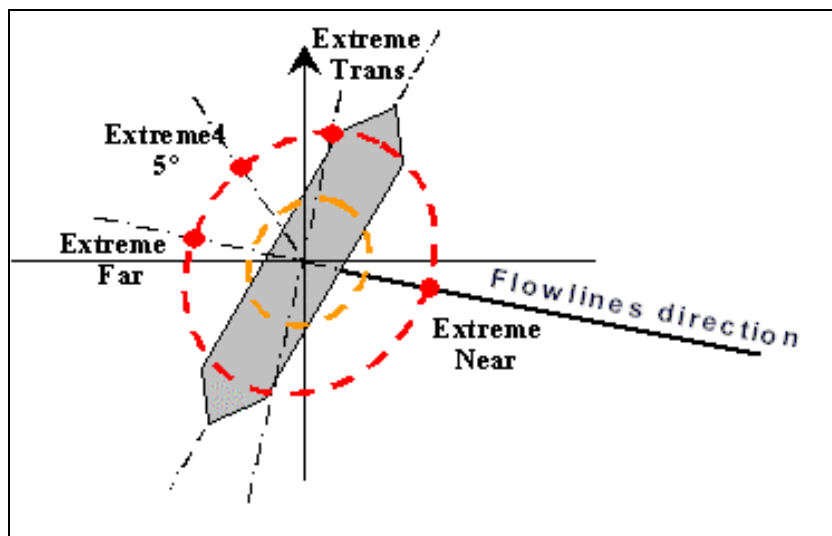
### 6.5.9 Corrosion allowance consideration

The FEA shall consider that the riser is not corroded except during the post-processing of the extreme and fatigue case when 50% of the corrosion allowance shall be deduced to take into account local decrease of the wall thickness.

## 6.6 Strength analysis

Strength analysis (in operating, extreme, accidental, test conditions) can be conducted using either regular or irregular waves. Regular wave analysis is a good preliminary design tool, as required design changes can be quickly evaluated. Regular wave analysis may be validated using irregular wave analysis, as the latter is able to provide a more realistic representation of the environment. If the wave period range is adequately addressed, regular wave analysis is sufficient for early feasibility checks.

At least 4 calculations for “trans”, “far”, “near” and “45° (incidence)” called positions shall be completed - see figure below for the definition of these terms.



Note: The objective of the strength analysis is also to define design loads for interface components such as FPS support and flexible joint.

## 6.7 Fatigue analysis

### 6.7.1 Generality

Fatigue assessment shall take account of the effects of wave action, FPS slow drift motions, vortex induced vibrations and any other phenomena (slugging...).

All aspects of the construction and installation of the SCR must also address the potential fatigue related failure modes.

The effects of these different sources of fatigue shall be combined along the length of the riser to determine the overall fatigue life.

### 6.7.2 Fatigue assessment

The following approach shall be adopted:

- A design factor of not less than 10 shall always be applied to the required service life of the SCR.
- SCR fatigue analysis is conducted using a stress-cycle (S-N) approach where the calculated stresses include mean stress corrections, thickness correction and/or stress concentration factors as appropriate.
- The fatigue shall be calculated on annual conditions with an intact mooring for the full life.
- The damage shall also be calculated for one year with a broken anchor line, i.e. this shall be used to assess anchorage repair and robustness philosophy of SCR design.
- The S-N curve shall be selected in accordance with the welding classification outlined in table 2.12-1 of [DNV RP C203](#). For the welded connections, designs have to differentiate between hot spot located on the inside of the pipe wall (root) or on the outside (cap). Typically, the 'D' curve in seawater + CP has to be used for the weld cap and the 'F1' curve in seawater (providing DNV tolerance requirements are met) for the weld root. However, as stated in section 1, emphasis shall be made on the production of high quality welds. As a

result, in practice, a class 'E' weld might reasonably be achieved and accepted for the weld root.

- The 'B' curve has to be used for parent metal as per U.K. Department of Energy Guidance Notes 1990.
- SCF shall be used for welded corrections and Goodman correction for base material.
- A minimum hi-lo of 1.00mm shall be used in the design calculations
- Any improvement in weld fatigue performance not demonstrated or quantified (effects of hydrostatic testing, weld grinding) shall not be accounted for in the design.
- The detrimental effect of the environment on fatigue resistance shall be estimated. Impact of temperature shall be quantified.
- Locally increased corrosion and subsequent impact on fatigue : potential increase in corrosion at low points where water collects (for eg TDP in a trench) shall be assessed and accounted for. Similarly, local increase in corrosion associated to increase in fluid speed shall be covered and analysed.
- Time domain irregular analyses including both wave frequency and low frequency motions together with rainflow counting assessment of fatigue damage shall be used, or frequency domain when calibrated against time domain result on the most critical bin.

### 6.7.3 High frequency plus low frequency fatigue assessment

#### Time domain

When time domain is used the fatigue shall be post-processed using the rain flow method.

The recommended approach for determining fatigue damage due to first and second order effects is to:

- Perform a dynamic time domain analysis of the riser subject to combined first and second order loads and motions for each seastate in the wave scatter diagram or condensed wave scatter diagram.
- Rainflow count the riser stress response.

It is understood that this may not be a practical approach depending on the level of detail required, criticality and time constraints. Hence, alternative statistical approaches may also be used.

The different methods and their suitability are discussed in detail in Appendix 10.

#### Frequency domain

A check of the fatigue post-processing when calculated in frequency domain shall be made (ensure that the distribution calculated in time domain is of Rayleigh type if Rayleigh is used to assess fatigue in frequency domain).

When low frequencies are close to wave frequencies, it is not recommended to sum the damages.

Summing low frequencies and wave frequency damages may be not conservative. It is recommended to check the processing of frequency domain method with time domain and rain flow.

#### 6.7.4 Fatigue improvement

Pipe alignment is critical to the life of the SCR girth welds. Therefore, it is beneficial to provide welders with dimensionally matched pipe ends. This is part of the overall process put forward to achieve high quality welds in the SCR.

Dimensionally matched pipe ends can be achieved by:

1. measure pipe ends and sort pipe to match ends
2. measure pipe ends and machine pipe ends to match them.

Methods to improve the fatigue performance of welds (e.g. machining pipe ends to provide accurate fit-up / reduced high-low) may be utilised subject to Company agreement on the effectiveness of such measures.

An engineering drawing defining where individual pipe joints are assigned along the riser and presenting all other dimension critical components (buckle arrestors, J-Lay collars) shall be produced. SCR construction shall be based on this drawing.

Specific attention shall be given to prepare measures so as to sort out the following issue: on seamless pipe, a tight pipe joint end tolerance does not guarantee any such tolerance away from the joint end. Thus, having to cut pipe joints during construction and installation will result in SCF bigger than the one used in the design. This will not be acceptable.

It is emphasised that the mechanical measurement of hi lo on closed bevels is extremely time consuming and requires measurements with close tolerances to be performed with limited access. This shall be accounted for.

#### 6.7.5 Fatigue distribution

Unless CONTRACTOR can correlate slow drift values and sea state, the fatigue analysis shall be performed from the same mean position (no fatigue distribution along the riser due to slow drift).

Fatigue damage at the TDP may be over estimated unless the time varying position of the TDP is accounted for.

This may be achieved using multiple analysis.

Alternatively a methodology for spreading VIV fatigue damage in the TDA, based on the fact that the TDP and riser system properties will vary over time, is given in Appendix 11.

#### 6.7.6 Weld fatigue testing and fracture mechanics assessment

See section 4.8.

Full scale tests shall be carried out to demonstrate that the weld design and welding procedure selected will exceed the level of fatigue resistance assumed in the design by a margin of not less than two standard deviations.

Fracture mechanics (FM) assessment shall be undertaken to develop flaw acceptance criteria for SCRs and to develop guidance for weld inspection techniques.

This is presented in Appendix 5.

### 6.7.7 Other sources of fatigue

In addition to first and second order fatigue and riser VIV, other possible sources of fatigue damage are:

- FPS VIV – FPSs with cylindrical sections subjected to current loading may oscillate due to vortex shedding; e.g. spars (usually straked to reduce this effect) and other deep draft floaters.
- FPS springing – small waves excite the tethers restraining the FPS which can cause VIV on the attached risers.
- Internal fluid effects such as slugging and pressure surges changing the internal fluid density causing riser motions.

This typically means that the fatigue damage is from the loading components and combinations identified above. Issues to be addressed when combining fatigue damage are:

- Correlation – the likelihood of simultaneous occurrence of fatigue generating effects.
- Stress amplification – the effect of two or more loading regimes occurring in combination
- Interaction – loading mechanisms may reduce the effect of stress amplification

## 6.8 VIV analysis

### 6.8.1 Generalities

The design of the SCR shall consider fatigue effects due to Vortex Induced Vibration.

The analysis of VIV and specification of suitable suppression devices is an iterative procedure which shall be undertaken using established software.

The effect of VIV suppression devices on riser diameter, mass, buoyancy, drag and inertia coefficients shall be assessed in the extreme storm analysis to ensure that the predicted riser response is representative and that the design fully satisfies the acceptance criteria.

The modelling of the riser shall also take into account any external coatings (thermal, corrosion protection and anti-fouling) specified in the design basis and shall examine the effects of marine growth on the response of the riser.

Since VIV damage is strongly correlated with pipe-soil modelling, the effect of seabed damping shall be taken into account when determining mode shapes for use in the VIV analysis. Similarly, when performing VIV fatigue analysis in the time domain (by mean of fully coupled simulation involving CFD or wake oscillators), advanced pipe-soil interaction modelling (see section 6.5.4.2 ) shall be used.

In some geographical locations special considerations may be required for extreme events, such as a 100 year submerged or loop / eddy current.

For these events the VIV fatigue analysis may be conducted in isolation of any other events with the predicted fatigue life required to be greater than an extended short term event in order to provide a check of robustness.

In addition, there have been some VIV due to vessel motion (Heave) observed in tests. Effect of these VIV on fatigue and on extreme response shall be assessed.

### 6.8.2 Total VIV fatigue damage

The critical parameters driving the fatigue induced by VIV shall be identified and submitted to COMPANY for approval. This activity shall help COMPANY to select the methodology to be used for defining current profiles distributions for the analysis. An iteration process shall be conducted to confirm the selected methodology. Validity range of the current profiles distribution selected shall be detailed (for e.g. Accuracy, duration of observation)

Competition between multi-modal and uni-modal response shall be assessed. The response inducing the highest fatigue damage shall be selected.

For the most dangerous current profiles and for the extreme currents, the riser response due to VIV shall be assessed by means of fully coupled time domain simulation of the fluid-structure interactions, and the corresponding damage shall be computed using rain flow counting method. The level of confidence of the VIV analysis shall be determined by comparing predicted life time by both approaches (modal and temporal).

Cumulated VIV and wave and low frequency fatigue shall also meet general requirement as stated in 6.7.2 .

The assessment of VIV fatigue shall be undertaken for current profiles both in the plane and normal to the plane of the riser.

The distribution of damage along the riser shall be assessed and added to fatigue damage arising from wave and slow drift motions.

The distribution of damage along the riser shall be assessed from the sum of the calculated fatigue damage for each current profile factored by the probability of occurrence.

Reference is made to Appendix 13 for VIV formulations.

### 6.9 Interference analysis

Clashing is not admitted. The tolerance is that the risk that the space between risers be less than two outer diameters shall be less than  $10^{-4}$  per design life.

An interference methodology shall be used with considering the case when a riser follows floating system displacements (mean, near, far, trans) and the adjacent riser is laterally jammed.

The interference methodology shall account for possible large displacements of the risers due to fluid-structure interactions occurring at large reduced velocity (or low mode numbers). VIV amplification and associated drag increase shall also be considered in the interference analysis.

Experimental analysis and CFD fully coupled fluid-structure simulations shall be performed to check the stability of the risers' array configuration and assess the damage increase.

Analysis shall be conducted to confirm that interference with other parts of the production system does not occur. The potential for interference between the following shall be assessed:

- Riser and FPS
- Riser and riser
- Riser and mooring lines
- Riser and umbilicals

The results of a clearance analysis can have an effect on the layout of the risers, umbilicals, mooring and orientation of the flow lines.

The layout of the risers shall also take into account the overall field layout, the requirement for discrete flow line corridors, anchor exclusion zones, crane locations and supply boat loading positions and the trajectory of dropped objects.

It may be that the layout is such that collisions between risers are inevitable.

In these circumstances, the cumulative probability of risers contacting other risers, umbilicals, mooring legs, the hull or any other obstruction during field life including installation shall not exceed  $10^{-4}$  per design life.

Furthermore, it shall be demonstrated that pressure and mechanical integrity is maintained in the event of collision.

### 6.10 Installation analysis

Installation operations shall be analysed to establish limiting values of wave height and current velocity/profile for each stage of the installation operations taking into account the likely duration of operations. Associated lay vessel motion limitation shall be determined. The vessel monitoring system shall allow adequate measurement of the above parameters.

The analysis shall also identify contingency procedures, temporary lay-down areas for the riser and emergency escape routes for all installation.

A fatigue assessment shall also be carried out to identify the proportion of fatigue life consumed due to installation operations.

This shall be taken into account in establishing the service life for the installed risers.

SCR installations tolerances (for e.g. TDP target box, flaring angle,...) shall be accounted for in the SCR design.

DNV OS-F201/ DNV OS-F101 local buckling score shall be provided at each node along the riser length. The riser model shall be refined at the riser top and at the TDA.

Transfer of the riser to the host FPS during final installation shall be engineered with extreme care taking into account the different load cases applying to installation (e.g., flooded riser, dynamics of lift FPS, effects of off-design configuration).

Installation equipment shall be specified based on the results of a dynamic analysis of installation operations and shall include substantial margins to account for the critical and non-standard nature of these operations.

### 6.11 Coupled analysis

The FPS, risers and mooring lines make up a global system, which may have a complex response to environmental loading.

The interaction of these components creates a coupled response, which may be significantly different to that predicted by treatment of each component individually.

Fully coupled analysis shall be conducted as part of the final riser verification.

It may be worth considering a coupled analysis at an early stage in the design process so that problems with the riser, FPS or mooring line design are highlighted as soon as possible and possible cost savings identified.

It is generally admitted that coupled analysis is not critical with a FPSO but is critical with a TLP.

Coupled analysis may influence roll.

## 6.12 Sensitivity studies

Sensitivity studies shall be carried out to confirm that the riser configuration continues to satisfy the design requirements as key parameters vary from selected values.

The sensitivity studies shall at a minimum include the following variables:

- Drag coefficient – over the range 0.6 to 1.2 for plain pipe with no expected occurrence of VIV, 0.6 to 1.8 for plain pipe with expected occurrence of VIV and up to 2.0 for pipe fitted with vortex suppression strakes
- Current profile velocity and direction
- The effectiveness of vortex suppression devices
- Wave periods corresponding to steepnesses ranging between 1:14 and 1:20 for storm waves. Where swell is a significant component, the sensitivity study shall also examine a corresponding range of swell periods
- Seabed characteristics : full sensitivity analysis of soil modelling parameters including soil stiffness and friction coefficients shall be investigated
- Structural damping between zero and a maximum of 0.15% of critical damping
- Adverse accumulations of tolerances in the position of the seabed end of the riser, the installed position of the host FPS and the effect of thermal growth on the transition from pipeline to riser
- Fluid density, wax deposition, marine growth
- Riser length, including installation tolerances, thermal expansion effects, tide and surge
- Weight, including corrosion, fluid density variations and slugging
- Wall thickness when fully corroded corresponding to end of life condition
- FPS motion (draught and mass distribution dependence)
- Flexible joint stiffness, including sensitivity to deflection, rate of deflection and temperature (usually the flexible joint stiffness is very high at low angle. These values shall be used to assessed fatigue at the top of the riser. Similarly the impact of mean stress on the stiffness shall be assessed, tested and used in the sensitivity analyses
- Ratcheting of the pipeline and effect on the mean position TDP laterally and axially shall be studied : this may impact fatigue and strength analysis and may lead to the necessity to anchor the line and use large bending radius close to TDZ

Expected extremes of the parameters identified above shall be incorporated into the riser model.

This will allow the effects of parameter changes to be quantified, and the robustness of the design to be assessed.

Based on the above sensitivity studies, CONTRACTOR shall demonstrate that the level of uncertainty is acceptable (Monte Carlo methodology).

## 7. Design requirements for SCR ancillary equipment

### 7.1 Flexible joints

Flexible joint characteristics shall include data for stiffness and damping over the range of expected operational temperatures.

These data shall also include stiffness characteristics at small deflections and low deflection rates.

The stiffness properties used in the SCR model shall conservatively represent the range of deflections predicted for each load cases.

The design analysis shall be carried out using values representative of the defined operational conditions including installation, hook-up and pressure testing with sensitivity checks to assess the effects of temperature and dynamic range on overall behaviour and fatigue life.

As for the mechanical characteristics,

- Test of ageing (seal, rotational stiffness) shall to be done if not fully qualified.
- Flexible joint shall be secured and “locked” during installation phase to ensure that large angular displacement is avoided during lay down, hang off, accidental deep off, etc.
- Flexible joint shall withstand the full water depth pressure loads.
- Flexible joint shall withstand decompression and recompression events occurring during production.

Measures shall be taken so as to ensure that the flexible joint can be replaced if damaged.

### 7.2 Stress joints

Taper stress joints may be used instead of flexible joint when high temperature and pressures resistance is required.

Stress joints shall be designed as an integral part of the riser system and the methodology adopted shall be documented and verified by tests.

The predicted fatigue life shall be not less than 10 times the specified service life.

Fatigue tests shall be conducted to confirm the fatigue life predictions.

The fatigue tests shall also demonstrate the long term adhesion and resistance to fatigue of any protective coatings applied to the stress joint.

### 7.3 Buoyancy

Buoyancy modules shall be modelled using densities appropriate to the operating depth and shall correctly take account of the mass of mounting clamps and/or straps.

The analysis shall identify the forces acting between the pipe and buoyancy device and shall show that sliding between the buoy and pipe is prevented for all identified load conditions including a safety factor of at least 1.2.

Damage to one buoyancy module shall not result in unacceptable loss of buoyancy for the riser system as a whole.

The effects of buoyancy loss of e.g. syntactic foam due to seawater absorption shall be assessed based on manufacturer's data.

Following the loss of 10% of the distributed buoyancy or the loss of one compartment in a subsea buoy / arch system, the configuration shall still be fit for purpose.

Materials such as syntactic foam shall be qualified by tests to confirm their resistance to hydrostatic pressure for the specified water depth.

Water absorption over the specified service life shall be documented and the end of life values used as a design check.

## 7.4 VIV suppression devices

The use of anti-VIV devices for SCRs might be considered by COMPANY provided that their efficiency are well documented and that their installation onto existing risers have led to positive results.

In any case, VIV mitigation devices for SCR application shall be qualified by tests in basin.

These tests shall be performed to confirm the structural resistance of the devices to hydrodynamic loading and to validate their impact onto the riser global behaviour.

VIV can be reduced using suppression devices such as strakes, fairings, and shrouds; of these the use of strakes is the favoured option.

Analysis shall account for effects of suppression devices on riser behaviour, via changes in weight and hydrodynamic coefficients, the table below.

| Parameter                                   | Typical value |
|---------------------------------------------|---------------|
| Normal drag coefficient, $C_{DN}$           | 1.4 – 3.0     |
| Tangential drag coefficient, $C_{DT}$       | 0.01          |
| Normal inertia coefficient, $C_{IN}$        | 2.0           |
| Tangential added mass coefficient, $C_{MT}$ | 1.0           |

Typical hydrodynamic parameters for straked riser pipe

## 7.5 Thermal coating or pipe in pipe

### 7.5.1 Thermal insulation

Thermal insulation may be required for certain production riser applications to avoid hydrate and wax formation and paraffin accumulation.

External thermal insulation such as syntactic foam can have a detrimental effect on the riser storm response due to increased drag loading and reduced weight / drag ratio.

PIP thermal insulation technology can be used to satisfy stringent thermal insulation requirements for catenary production risers whilst maintaining an acceptable dynamic response.

### 7.5.2 Inner – outer pipe interaction

The inner and outer pipes of a PIP system may be connected via bulkheads at regular intervals. Bulkheads limit relative expansion and can separate the annulus into individual compartments.

The use of bulkheads, whilst providing a good solution for pipelines, may not be acceptable for dynamic SCRs, as it may introduce high stress concentrations and fatigue damage and result in a significant increase in heat loss.

For analytical purposes, this type of PIP may be modelled as a single pipe but special attention shall be paid to residual stresses and curvatures in the inner pipe resulting from manufacturing and installation processes.

As an alternative to bulkheads, regular spacers may be used that allow the inner and outer pipes to slide relative to each other whilst maintaining concentricity.

For both types of PIP, the designer shall address operation and installation issues.

### 7.5.3 Operation

The following events during operation shall be considered:

- Relative motion of the two pipes in the axial direction
- Axial force due to thermal expansion and internal pressure
- Buckling of the inner pipe
- Stresses in each pipe caused by the centralisers

### 7.5.4 Installation

The following events during installation shall be considered:

- Consumed fatigue life of each pipe
- Residual stresses in the pipe wall due to large curvature history
- Residual axial forces between the two pipes
- Length and play of the centralisers

In the case of reel-laid PIP risers, the effect of the plastic deformation due to the reeling process shall be assessed and cross-section distortion (i.e. ovalization) minimised.

The pipe yields as it is reeled and it is at its weakest, most vulnerable state at the reel contact point.

The influence of PIP centralisers on the resulting pipe geometry as a consequence of reeling and straightening shall also be assessed.

Reeling considerations will determine the maximum length between centralisers.

## 7.6 Anode attachment

If possible anode shall not be attached on dynamic part of the pipeline.

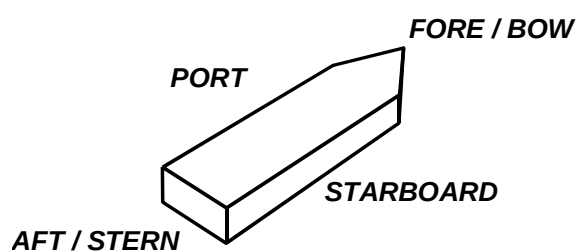
If this is not possible anode shall be located in the sections which are not subject to fatigue.

Particular attention shall be given to anode attachment (this will require fatigue testing as the weld procedure).

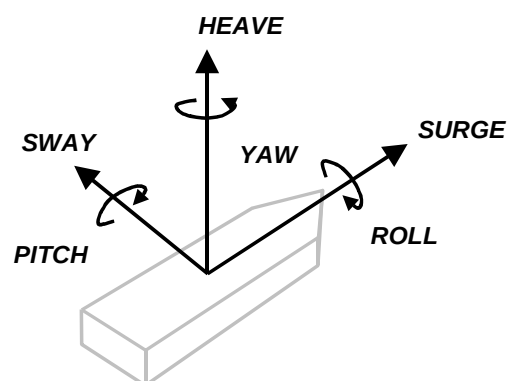
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- [14] Fatigue Design and Performance Verification of Deepwater Risers – OMAE 2003-37492 – Jaime Buitrago, Michael S. Weir and Wan C. Kan
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## Appendix 2 FPS motion convention



**FPS orientation**



**FPS axis definition**

The motion and phase conventions shall be taken as follows:

- Right-handed coordinate system
- Wave elevation positive upwards
- Surge positive toward bow
- Sway based on a right-handed system
- Heave positive upwards
- Roll positive starboard down
- Pitch positive bow down
- Yaw positive bow to portside

## Appendix 3 Geotechnical data

In all cases, these data shall relate to both undisturbed soils and to soils that have been worked extensively by the action of the riser which may result in disturbed or loaded soil to a depth of several pipe diameters.

Data presented shall include upper and lower bounds representing reasonable assessment of the likely variability of the soil condition and of the uncertainties arising from the sampling and testing process.

Range of soil parameters values required for modelling interaction of the riser with the seabed are given below:

| Parameter                             | Units                   | Range                         |
|---------------------------------------|-------------------------|-------------------------------|
| Undisturbed shear strength, $S_u$     | (kPa)                   | TBA                           |
| Sensitivity of clay                   | (-)                     | TBA                           |
| Shear strength gradient with depth    | (kPa/m)                 | TBA                           |
| Submerged unit weight, $\gamma'$      | (kN/m <sup>3</sup> )    | 2.0 – 10.0                    |
| Poisson's ratio, $\nu$                | (-)                     | 0.4 – 0.6                     |
| Voids ratio, $e$                      | (-)                     | 0.5 – 4.0                     |
| Plasticity index, $I_p$               | (%)                     | 20 – 80                       |
| Lateral friction coefficient, $\mu_L$ | quasi- static<br>cyclic | (-)<br>0.1 – 1.0<br>0.1 – 1.5 |
| Axial friction coefficient, $\mu_A$   | quasi- static<br>cyclic | (-)<br>0.0 – 0.6<br>0.0 – 0.5 |

### Range of geotechnical parameters for clay

| Parameter                             | Units                | Range       |
|---------------------------------------|----------------------|-------------|
| Submerged unit weight, $\gamma'$      | (kN/m <sup>3</sup> ) | 8.0 – 10.0  |
| Angle of friction $\phi'$             | (°)                  | 30 – 40     |
| Poisson's ratio, $\nu$                | (-)                  | 0.30 – 0.40 |
| Voids ratio, $e$                      | (-)                  | 0.4 – 2.0   |
| Lateral friction coefficient, $\mu_L$ | (-)                  | 0.0 – 0.6   |
| Axial friction coefficient, $\mu_A$   | (-)                  | 0.0 – 0.6   |

### Range of geotechnical parameters for sand

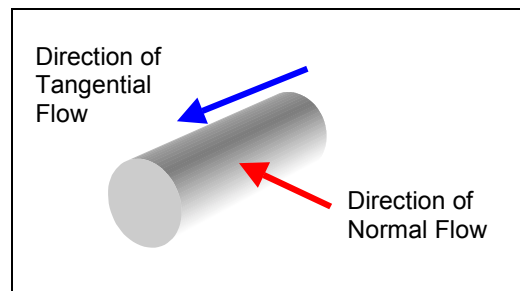
## Appendix 4 Hydrodynamics

### Hydrodynamic factors

The hydrodynamic parameters used in SCR analysis are given in the table below with typical values for bare riser pipe. The directions of the normal and tangential coefficients are shown in figure below. The hydrodynamic properties for strakes are discussed in section 10.6.

| Parameter                                   | flow regime                 |                                |                               |
|---------------------------------------------|-----------------------------|--------------------------------|-------------------------------|
|                                             | Sub-critical<br>$Re < 10^5$ | Critical<br>$10^5 < Re < 10^6$ | Super-critical<br>$Re > 10^6$ |
| Normal drag coefficient, $C_d$              | 1.2                         | 0.6-1.2                        | 0.7                           |
| Tangential drag coefficient, $C_{dT}$       | 0.01                        |                                |                               |
| Normal inertia coefficient, $C_m$           | 2.0                         |                                |                               |
| Tangential added mass coefficient, $C_{at}$ | 1.0                         |                                |                               |

### Typical hydrodynamic parameters for bare riser pipe



Direction of normal and tangential coefficients

### Tangential flow

The tangential drag of a riser is typically small as the structure is slender and the outer profile is even. Buoyancy elements, other appurtenances such as strakes, or marine growth can result in a local increase of the tangential drag coefficient and added mass coefficient.

### Keulegan-Carpenter number

The Keulegan-Carpenter number provides and measures the effects of flow velocity variation. The flow velocity definition depends on the prevailing flow conditions:

#### Regular (sinusoidal) flow

$$K_C = \frac{U_m T}{D} \quad (2)$$

where

$U_m$  velocity amplitude of the flow

$T$  wave period

$D$  hydrodynamic riser diameter

#### Irregular flow

$$K_C = \frac{\sqrt{2} U_{RMS} T_P}{D} \quad (3)$$

where

$U_{RMS}$  root-mean-squared (RMS) irregular

fluid flow approach velocity

$T_P$  peak spectral wave period

## Appendix 5 Engineering Critical Assessment

### Unstable fracture

The analyses shall result in an envelope of limiting crack sizes, which cause failure under the combination of expected extreme event (e.g. 100 year return period hurricane) and normal operating conditions for a particular riser. Analysis shall consider the application of extreme events at the beginning and at the end of life whichever is the most damageable case.

The CTOD defined in the Project Specification shall be used in the calculations.

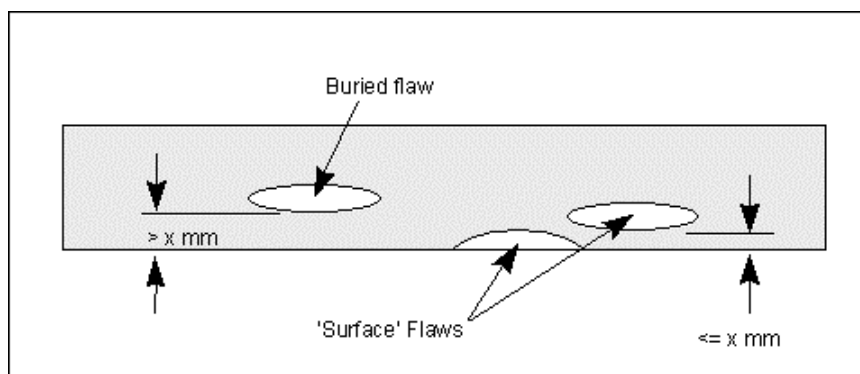
Engineering Critical Assessment (ECA) shall be carried out according to Level 2 of [BS 7910](#) taking into account plastic-collapse and brittle fracture modes of failure

Conservative values shall be used to properly account for weld/parent metal mismatch.

If the installation process involves plastic deformation, specific ECA shall be conducted using fully validated tool and project specific data.

Surface breaking, buried, and interacting flaws shall be considered.

An idealisation of the elliptical surface and buried flaws is shown below.



When the un-cracked ligament of a buried flaw ( $x$ ) is equal or less than the flaw height ( $a$ ) then the buried flaw shall be re-characterised as a surface flaw.

Stress intensity factors must be chosen so that the analytical solution accurately mimics the cracked pipe. In many cases, flat plate solutions provide sufficiently accurate results.

However, for cases where the crack length and depth are not small with respect to the pipe circumference and wall thickness, the far-field uniform stress plate solutions may be inaccurate.

Moreover, thin shells with outer to inner radii greater than 0.8, require curvature correction factors.

### Fatigue crack growth

Paris Law gives the growth rate of crack of depth at  $N$  applied stress cycles, as follows:

$$\frac{da}{dN} = A(\Delta K)^m \quad (1)$$

where

$\Delta K$  stress intensity factor range

$A$  material specific constant

$m$  material specific constant

BS 7910 (1999) provides recommended parameter values for using the Paris law. Material / weld metal / HAZ specific data obtained from tests are relatively inexpensive and may be used in-lieu of codified data. Stress concentration factors (SCF's) shall be applied to all stress range bins.

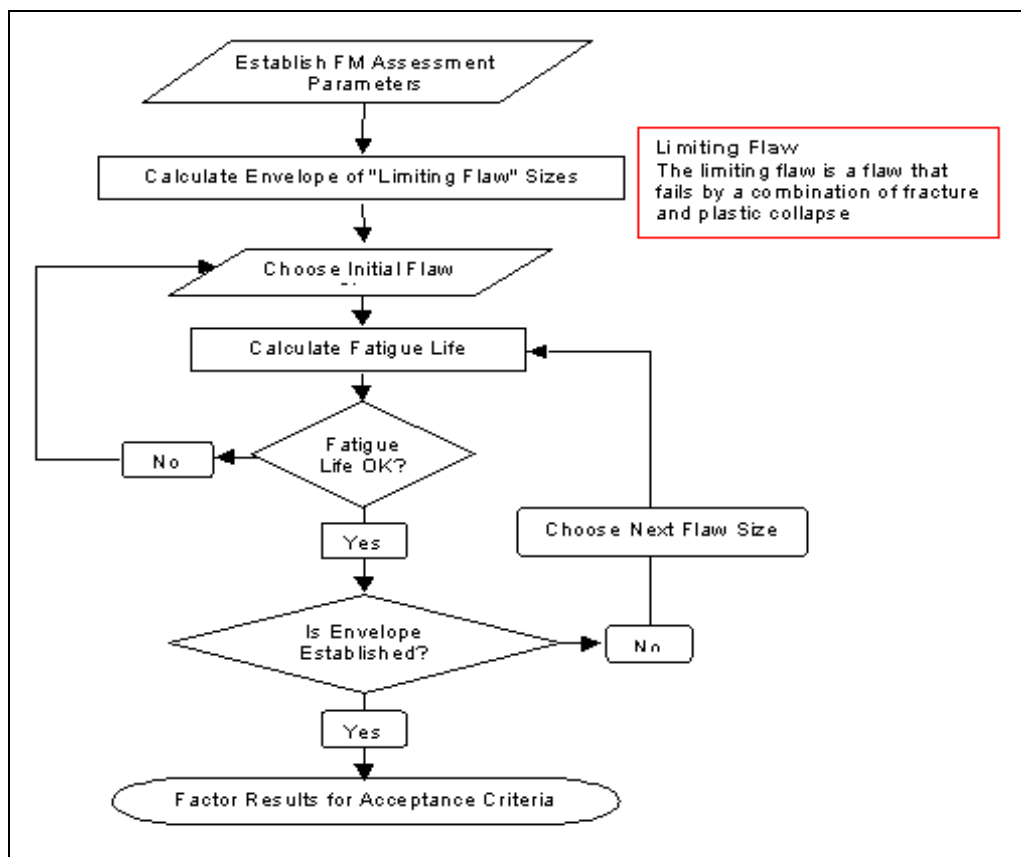
Factors to consider are:

- Internal contents: crack growth may be accelerated in hydrogen bearing environments, i.e. H<sub>2</sub>S or other corrosive conditions
- Cathodic protection: crack growth is dependent on the level of corrosion potential protection expressed in mV with respect to a reference electrode
- Hydrogen embrittlement issues related to the introduction of contamination (i.e. moisture, grease, etc) from poor house-keeping during welding
- Plastic straining (for reel-laid risers)
- Internal pressure effects on crack growth
- Effect of temperature

Confirmation of acceptance criteria based on proven properties shall be achieved.

### Acceptance criteria

The next figure shows a schematic of an acceptance criteria development procedure.





The approach has been to develop curves representing an envelope of elliptical cracks (surface or embedded flaws), which may grow to or exceed the calculated limiting flaw size in a specified time period.

The related time period is referred to as the design life and is established as a function of safety factor multiplied by the service life.

Deciding the safety factor is subjective but must take into account the type and sensitivity of the selected inspection technique used to evaluate the riser girth welds.

It has been advised that no specific philosophy exists with respect to selecting the degree of safety, however the main emphasis is to establish the maximum flaw dimensions that can be reliably detected and will survive the factored design life.

Typical values of safety factor applied to the service life related to evaluating resistance to fracture, is between 3 to 5.

Parametric analysis shall be conducted to understand sensitivity to critical parameters (e.g. SCF). As a result, the final acceptance criteria shall not be influenced by small variations in the critical parameters.

All sources of cyclic stresses shall be included in the assessment (e.g. VIV).

External surface flaws typically result in a more stringent requirement than internal flaws. This is predominantly due to the occurrence of higher stresses at the outer surface compared to the inner surface under bending loads. This shall be accounted for.

Probabilistic fracture mechanics is currently being used to assist in developing a consistent methodology for an acceptance criteria that when coupled with automated ultrasonic testing (AUT), shall result in a more consistent approach.

### **Influence of construction / installation method on fatigue life**

The in-service requirements are directly related to weld quality, acceptable levels of mismatch between pipe ends and out-of-roundness, whilst non-destructive examination (NDE) requirements with respect to detecting critical flaws are determined from fatigue life and fracture analysis assessments. In particular:

- SCFs from geometric discontinuities shall be quantified, with regard to pre-weld fit up (hi-lo) limits resulting from out of roundness (ovality), non-uniform wall thickness (seamless pipe) and tolerances of weld preps.
- Weld procedure can affect material properties and residual stresses.

### Typical acceptance criteria

Established for 10" pipe:

#### Surface- breaking defect acceptance criteria

| Joint description   | Surface defect height<br>(mm) | Allowed length<br>(mm) |
|---------------------|-------------------------------|------------------------|
| Critical joints     | 0.0 – 0.5                     | 25                     |
|                     | 0.51 – 1.0                    | 15                     |
|                     | > 1.0                         | 0                      |
| Non critical joints | 0.0 – 1                       | 25                     |
|                     | 1.0 – 2                       | 15                     |
|                     | > 2.0                         | 0                      |

#### Embedded defect acceptance criteria

| Joint description   | Surface defect height<br>(mm) | Allowed length<br>(mm) |
|---------------------|-------------------------------|------------------------|
| Critical joints     | 0.0 – 0.8                     | 50                     |
|                     | 0.81 – 1.5                    | 25                     |
|                     | 1.51 – 2.5                    | 10                     |
|                     | > 2.5                         | 0                      |
| Non critical joints | 0.0 – 1.1                     | 50                     |
|                     | 1.1 – 2.5                     | 25                     |
|                     | 2.51 - 3 ( see nota below)    | 10                     |
|                     | > 3 ( see nota below)         | 0                      |

Nota: interacting defect only – single defect vertical height limited to 3.0 mm



## Appendix 6 Riser – soil interaction

Guidelines evaluating the different method to calculate vertical pipe – soil interaction will be include in the next revision of this specification.

## Appendix 7 Special material

Titanium or composites may be used as alternatives to steel in catenary riser applications.

Titanium is more flexible, stronger and lighter than steel and has been used for stress joints to reduce interface loads and to extend SCR feasibility to shallower water or geographical locations with more severe environmental conditions.

Lower weight reduces top tension in deep-water applications but could introduce performance disadvantages. Typical titanium properties are given in the table below.

The disadvantage of titanium is the higher material cost and potential difficulties in offshore welding, although this latter point is becoming less significant with the introduction of more advanced / adaptable automatic welding systems.

Titanium is proven for offshore applications having been used in drilling risers and stress joints.

A design consideration of titanium is that its yield strength is more sensitive to high temperatures than steel; the reduction is greater than that of steel.

| Parameter              | Units                | Typical Value                               |
|------------------------|----------------------|---------------------------------------------|
| 0.2% Proof Stress      | (MPa)                | 828                                         |
| Tensile Strength       | (MPa)                | 897                                         |
| Young's Modulus, E     | (kN/m <sup>2</sup> ) | 105x10 <sup>8</sup> - 120x10 <sup>8</sup>   |
| Poisson's Ratio, $\nu$ | (-)                  | 0.31                                        |
| Shear Modulus, G       | (kN/m <sup>2</sup> ) | 40.1x10 <sup>8</sup> - 45.8x10 <sup>8</sup> |
| Density, $\rho$        | (kg/m <sup>3</sup> ) | 4420                                        |

### Typical titanium material properties (ASTM grade 23)

Composite materials are relatively unproven except for a number of drilling riser joints integrated in the Conoco Heidrun drilling riser.

Development programmes are ongoing for various riser applications, but qualification testing, reliability and suitability for the proposed applications all need to be assessed before composite materials can be used with confidence.

## Appendix 8 Riser pipe property

The symbols used in the equations for riser pipe geometry are given below with a cross-section of a typical riser given in Figure A8.1. The unit system shall be consistent (SI).

| Equations for Geometric Properties of Pipe |                                            | Definitions                                        |
|--------------------------------------------|--------------------------------------------|----------------------------------------------------|
| Internal riser pipe diameter               | $D_I = D_O - 2t$                           | $A$ total cross-sectional area displaced           |
| Area of Steel                              | $A_S = \frac{\pi}{4} (D_O^2 - D_I^2)$      | $D_E$ external diameter of coatings and insulation |
| pipe bore cross-sectional area             | $A_I = \frac{\pi}{4} D_I^2$                | $D_O$ outer riser pipe diameter                    |
| Area of Insulation and coatings            | $A_E = \frac{\pi}{4} (D_E^2 - D_O^2)$      | $g$ acceleration due to gravity                    |
| Total cross-sectional area                 | $A = \frac{\pi}{4} D_E^2$                  | $h$ height above the seabed                        |
| "In Air" Mass per unit Length              | $m = A_S \rho_S + A_F \rho_F + A_E \rho_E$ | $p_S$ shut in pressure                             |
| Mass of Displaced Water                    | $m_D = A \rho_W$                           | $t$ riser pipe wall thickness                      |
| "In Water" Mass per unit Length            | $m_S = m + C_a m_D$                        | $T$ true wall tension                              |
| Mass Ratio                                 | $\mu = \frac{\pi}{4} \cdot \frac{m}{m_D}$  | $w_A$ weight in air per unit length                |
| Weight in Air                              | $w_A = mg$                                 | $w_S$ submerged weight per unit length             |
| Submerged Weight)                          | $w_S = w_A - m_D g$                        | $\rho_E$ density of the insulation                 |
| Second Moment of Area                      | $I = \frac{\pi}{64} (D_O^4 - D_I^4)$       | $\rho_F$ density of the internal fluid             |
| Polar Second Moment of Area                | $J = 2I$                                   | $\rho_S$ density of riser pipe material            |
| Polar Inertia                              | $p = 2I \rho_S$                            | $\rho_W$ density of seawater                       |
| Radius of Giration                         | $r = \sqrt{\frac{I}{A_S}}$                 |                                                    |
| Equations used in SCR Analysis             |                                            |                                                    |
| Shear Modulus                              | $G = \frac{E}{2(1+\nu)}$                   |                                                    |
| Effective Tension                          | $T_{eff} = T - p_I A_I + p_E (A_S + A_I)$  |                                                    |
| Internal Pressure                          | $p_I = p_S + \rho_F gh$                    |                                                    |
| External Pressure                          | $p_E = \rho_W gh$                          |                                                    |

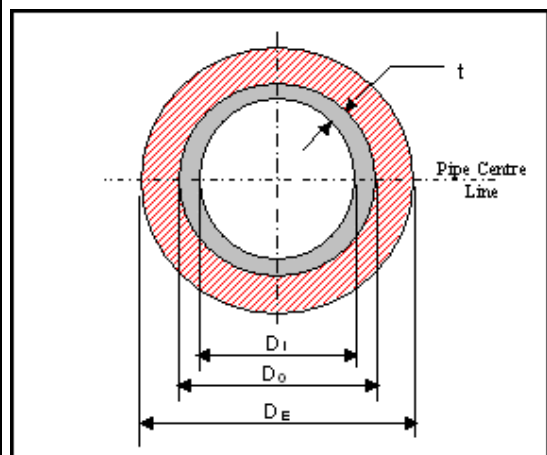


Figure A8.1 – Cross-section of Riser Pipe



## Appendix 9 Meteocean data

### Wave, swell data

The following data are required and shall be presented separately for waves, storm waves and swell:

- Wave heights expressed as extreme values corresponding to 1, 10 and 100 year return periods.
- The wave heights shall be broken down to show the design values from each of eight equal sectors around the compass as well as omni-directional maxima.
- Waves associated with extreme currents.
- Wave spectrum.
- The relationship between  $T_p$  and corresponding values of  $H_s$ ,  $H_{max}$ .
- Long-term wave loading defined by a  $H_s$ - $T_p$  joint probability diagram showing the number of waves occurring with a characteristic combination of height and period.
- The data in this diagram shall be grouped into bins representing increments of wave height/period of 0.5m  $H_s$ /1 sec  $T_z$  and shall include clear indications of directionality (ie showing the distribution between eight equal sectors around the compass).

Error in a wave height accuracy shall be included in the design in a conservative manner.

The wave spectrum for fully developed seas shall be defined preferably in terms of either the JONSWAP (limited fetch), Pierson-Moskowitz or site specific spectrum.

Representativeness of the spectrum shall be demonstrated and reviewed by CONTRACTOR.

### Current

The following current data are required and shall be presented as consistent sets of velocity, height and direction data:

- Extreme current profiles corresponding to 1, 10 and 100 year return periods.
- These data shall be broken down to show the design values from each of eight equal sectors around the compass as well as omni-directional maxima.
- Current profiles shall comprise surface and seabed values together with values at minimum eight equally spaced intervals through the water column.
- These profiles shall include directional data as noted above.
- Currents associated with extreme waves.
- Long-term current data defined in terms of exceedence probabilities and yearly occurrences.

The data shall represent the statistically most probable values and shall include figures for standard deviations or a statement of confidence limits.

The data shall also identify the separate, independent components contributing to the overall profile and provide data for each of these components relating to directional distribution, most probable values for design, return periods and persistence (together with figures for standard deviations or confidence levels).



The data shall also identify the most probable combinations of these components and the probability of simultaneous occurrence of design maxima.

Error of current velocity accuracy shall be included in the design in a conservative manner.

### **Marine growth**

Details shall be provided of marine growth at various levels through the water column. In addition, oxygen content measurements of the seawater shall be taken at intervals through the water column to the seabed to support reasonable assumptions with regard to marine growth.

Note that marine growth has been observed on risers installed in depths exceeding 450 m. Oxygenation of the water down to the seabed has also been observed due to internal waves/tumbling of the water column.

## Appendix 10 Sea states

The random nature of the ocean's surface means that it can only be quantified statistically. Generally the oceans surface does not change considerably over a period of 3 hours.

This sea-state may be described in terms of:

- Significant wave height,  $H_s$  – the average height of the highest one third of the waves within a sea-state
- Mean zero crossing period,  $T_z$  – the mean time between up-crossing of the mean water level

Individual sea-states can be represented in two ways:

- Regular waves – comprising of a single wave height and period
- Irregular waves – a statistical representation of the individual wave conditions which exist during a particular time period (usually 3 hours)

### Regular waves

Regular waves typically assume a sinusoidal wave consisting of the maximum wave height,  $H_{\max}$ , and maximum period,  $T_{\max}$ .

Wave height is generally considered to be Rayleigh distributed and the most probable maximum wave height is evaluated using:

$$H_{\max} = H_s \sqrt{0.5 \ln N} \quad (1)$$

where  $H_{\max}$  most probable max. wave height in a design storm  
 $H_s$  significant wave height for a design storm  
 $N$  number of wave crests in a design storm

For example, in a storm of three hours duration, with a wave elevation mean zero-upcrossing period  $T_z = 10.8$  seconds, the number of wave crests is 1,000 and maximum wave height is:

$$H_{\max} = 1.86 H_s \quad (2)$$

The period  $T_{\max}$  associated with  $H_{\max}$  may be taken as the peak spectral period  $T_p$ . The ratio  $T_p/T_z$  depends on the wave spectrum, but is given for two particular cases:

Pierson-Moskowitz:  $\frac{T_p}{T_z} = 1.40 \quad (3)$

JONSWAP (if  $\gamma = 3.3$ ):  $\frac{T_p}{T_z} = 1.28 \quad (4)$

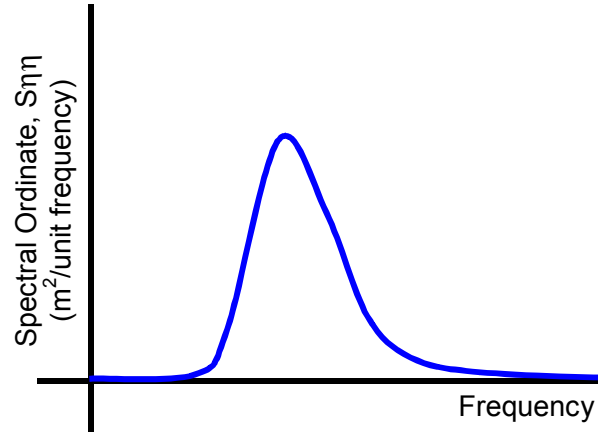
## Irregular Waves

Irregular waves are a statistical representation of a sea-state and may be described using a wave energy spectrum.

Wave energy spectrum is generally given in terms of frequency,  $T$  and spectral ordinate,  $S_{\eta\eta}$  - as represented in the typical graph.

The wave energy spectrum can be represented using, among others, Pierson-Moskowitz, JONSWAP (Joint North Sea Wave Project) or Ochi-Hubble equations.

A graphical representation of these spectrae is shown on the next page.



**Pierson-Moskowitz** (is JONSWAP with  $\gamma = 1$ )

$$S_{\eta\eta} = \frac{H_s^2}{4\pi T_z^4 f^5} e^{\left(\frac{-1}{\pi T_z^4 f^4}\right)} \quad (5)$$

where:

$S_{\eta\eta}$  spectral ordinate  
 $f$  frequency

## JONSWAP

$$S_{\eta\eta} = \frac{\alpha g^2}{(2\pi)^4 f^5} e^{\left(\frac{-5}{4} \left[\frac{f}{f_p}\right]^4\right)} \gamma^A \quad (6)$$

$$A = e^{\left(\frac{-(f/f_p - 1)^2}{2\sigma^2}\right)} \quad (7)$$

where :

$\alpha$  Phillips constant  
 $f_p$  peak spectral frequency  
 $\gamma$  peaked-ness parameter

## Ochi-Hubble

$$S(\omega) = \frac{1}{4} \frac{\left[ \frac{(4\lambda + 1)\omega_p^4}{4} \right]^\lambda}{\Gamma(\lambda)} \frac{H_s^2}{\omega^{(4\lambda+1)}} \times \exp \left[ - \left( \frac{4\lambda + 1}{4} \right) \left( \frac{\omega_p}{\omega} \right)^4 \right] \quad (8)$$

$$S_{\eta\eta} = 2\pi S(\omega) \quad (9)$$

where

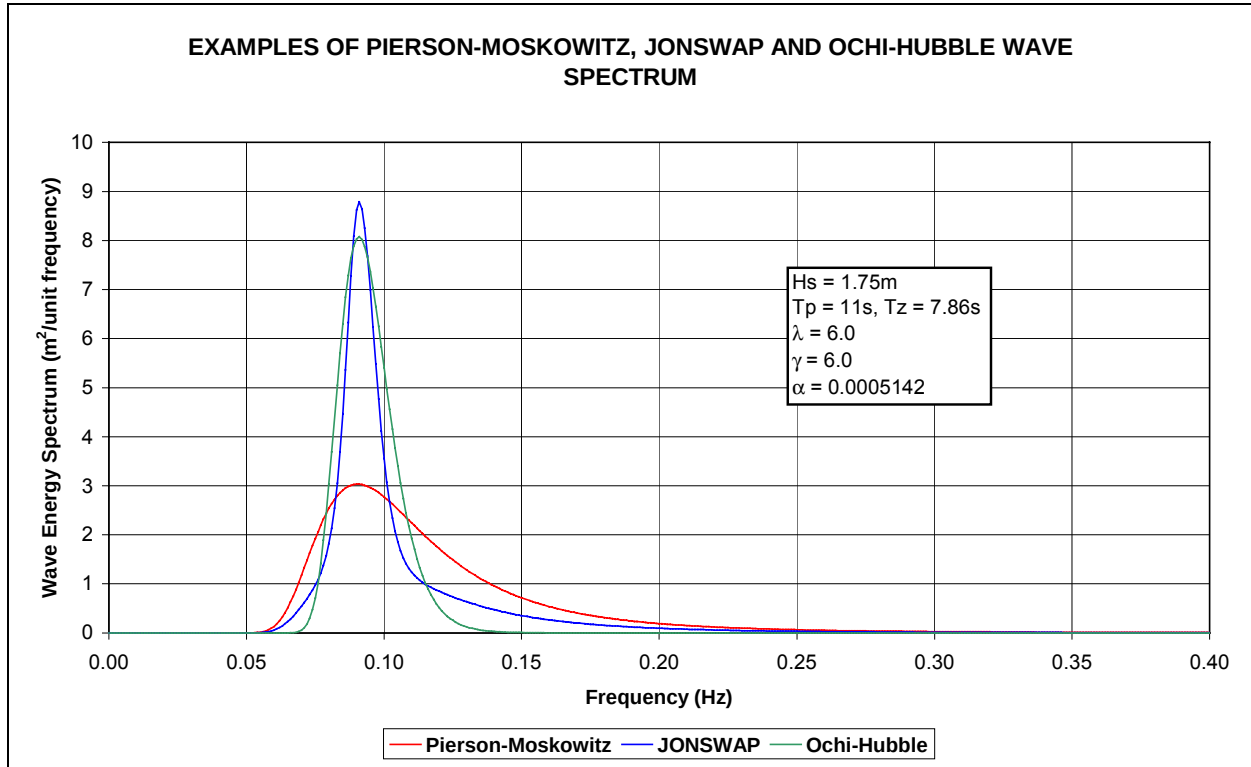
$\omega$  radian frequency,  $\omega = \frac{2\pi}{T}$

$\omega_p$  radian frequency,  $\omega_p = \frac{2\pi}{T_p}$

$\lambda$  peak enhancement factor

$\Gamma(\ )$  gamma function

## Comparison of Wave Spectrum



## Binomial Wave Spectrum

A binomial wave spectrum may be used to model both sea (high-frequency) and swell (low-frequency) seastates.

A binomial spectrum may have two distinct peaks corresponding to the peak sea and swell frequencies, if the energy of the two spectra is comparable. The total combined sea and swell spectrum may be developed by adding the individual sea and swell spectra, as below:

$$S_{Total}(f) = S_{Sea}(f) + S_{Swell}(f) \quad (10)$$

The total significant wave height due to the sea and swell is the square root of the sum of the squares of the sea and swell significant wave heights, as below:

$$H_{S,total} = \sqrt{H_{S,Sea}^2 + H_{S,swell}^2} \quad (11)$$

## Extreme Response of Irregular Waves

There is sometimes a need to post-process sample irregular dynamic analysis results (or measurements) in order to establish an extreme response prediction.

Alternatively, the sample extreme may be considered a good enough estimate.

Possible approaches are:

- Assume the calculated extreme, direct from the time-history (regular or irregular), is valid
- Assume a Rayleigh distribution for the response peaks, see below
- Assume a general distribution for the peaks, see below

## Rayleigh Distribution

Assume a Rayleigh distribution for the response peaks and use the following equation:

$$X_{\max} = X_{\text{mean}} + \left[ 2 \ln \left( \frac{N}{p} \right) \right]^{\frac{1}{2}} \sigma \quad (\text{for small } p \text{ only})$$

where  $p$  probability of exceedance in  $N$  peaks  
 $p = 1$  is often considered as an appropriate value  
 $\sigma$  is the standard deviation of the parent process  $X$

This method is strictly only valid when the parent process is Gaussian and the response is narrow-banded, though for many random processes in offshore engineering these are reasonable assumptions.

A predominant riser loading mechanism, drag, is non-linear – meaning that the parent process could be significantly non-Gaussian.

Also, riser response can contain widely separated frequencies associated with different loading mechanisms; e.g. slow-drift, wave-frequency and riser VIV components, so the Rayleigh assumption has to be used with care.

## General Distribution

Assume a general distribution for the peaks; e.g. three-parameter Weibull, whose pdf is:

$$p(Y) = \left( \frac{c}{b} \right) \left( \frac{Y - a}{b} \right)^{c-1} \exp \left[ - \left( \frac{Y - a}{b} \right)^c \right]$$

with  $Y > a, b > 0, c > 1$  and where  $Y$  is a peak of the parent process  $X$ .

Parameters  $a, b$  and  $c$  must be determined in each case, making the Weibull distribution harder to use than the Rayleigh distribution (where only one parameter is required, namely the standard deviation of  $X$ , which can readily be estimated with good accuracy).

The Weibull parameters may be estimated by a recognised method; e.g. maximum likelihood or moment method.

## References

Butterworth, N.D.P. & Adams, A.J. – “Dynamics of Fixed Marine Structures”, Third Edition, Thomson Litho Ltd, East Kilbride, Scotland, 1991

## Appendix 11 Calculation Of Riser Fatigue Damage

### Introduction

For risers on an FPS there are usually three sources of fatigue damage:

- First order motions – Wave-frequency loads and motions (~12s)
- Second order motions – Low-frequency motions of the FPS induced by slowly varying wave drift and wind and, for spars, vortex-induced vibration (~100s)
- Riser VIV due to current or FPS heave

Typically first and second order fatigue effects shall be considered in combination whilst the damage from VIV is determined separately. This section describes the analysis approaches considered suitable for determining the fatigue damage due to first and second order effects.

### Fatigue Calculation Methods

Three methods used to calculate and combine the first and second order fatigue damages are given below in order of preference:

Method 1: Analyse the combined first and second order motions in time-domain and determine fatigue damage using the rain-flow counting approach. Requires the use of time domain analysis.

Method 2: Derive response spectra for combined first and second order effects. Apply statistics to determine the total fatigue damage

Method 3: Determine fatigue for first and second order effects separately, factor the fatigue damages and combine to give total fatigue damage

Methods 2 and 3 may be conducted using either time or frequency domain analyses although for SCR analysis time domain is the recommended method.

These methods will be described in more detail further on.

It is recognised that many influences come in to play in selecting a method – including:

- Domain and format of riser stress data
- Available software
- Available time
- The relative importance of different terms
- The required accuracy at a particular stage in a particular project

However, as a design moves in to final detailed design there will be a strong expectation that RFC will be used unless comfortable margins of safety are demonstrated.

The use of combined stresses; i.e. LF and wave-frequency components calculated in the same dynamic analysis, is preferred, and the level of accuracy shall be commented on in all cases.

Other methods are possible. For example, all of the above assume a irregular dynamic analysis is performed. Regular wave analysis may be sufficient in some cases, especially where fatigue is not a governing criterion; it may also enable more rapid design evolution.

Similarly, although time-domain analysis is generally regarded as essential for extreme and confirmatory assessment of SCRs, enhanced frequency domain analysis may have a part to play in feasibility studies, parameter studies and fatigue estimation.

### Method 1

With method 1 the first and second order motions are combined, then the fatigue damage is calculated using rain-flow counting as illustrated in Figure 1.

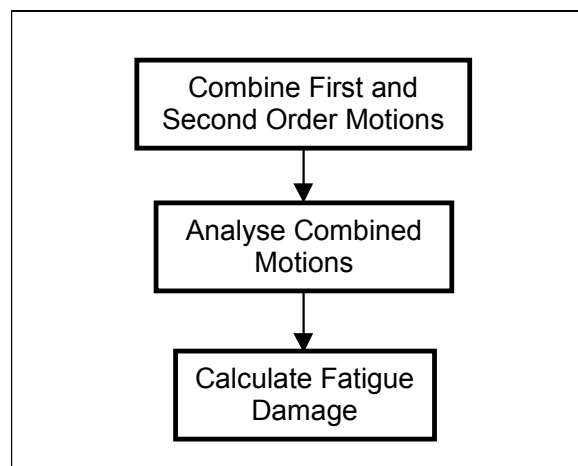


Figure 1 – Rain-flow Counting Fatigue Method.

The rain-flow counting fatigue method for first and second order motions is given in the steps below:

The optimum approach is to conduct the analysis for every sea-state in the scatter diagram. This may be too time consuming and so if necessary, condense scatter diagram to manageable number of fatigue sea-states; eg.10-20.

For each sea-state, apply mean offset and conduct non-linear time-domain analysis with FPS second order motions included.

Combine tension and bending to obtain total stress

Rain-flow count total stress time-traces to get fatigue damage due to each sea-state at points around circumference and along riser length.

Multiply damage by probability of occurrence of bin and sum over bins.

Repeat for required number of loading directions and sum for total damage

### Method 2

With method 2 the stress response spectra is derived for combined first and second order effects and statistics used to determine the total fatigue damage. The following statistical methods are available:

Assume a Rayleigh distribution for the stress peaks. This can overestimate fatigue damage unless stress is highly narrow-banded.

Use a bimodal method. A method by Jiao and Moan [1] is valid when bimodal peaks of the stress spectrum are distinct and well separated.

A number of investigators have developed correction factors to the Rayleigh approach; e.g. Wirsching and Light [1], Ortiz and Chen [2], Lutes and Larsen [4] [5]. The most accurate and

most easily applied of these methods is the single moment method of **Lutes and Larsen**. A comparison of the various methods, including the bimodal method of Jiao and Moan [1], is given in [5].

The method is given in the steps below:

The optimum approach is to conduct the analysis for every sea-state in the scatter diagram. This may be too time consuming and so if necessary, either a condensed scatter diagram or linearisation sea-states may be used as described for methods 1 and 3 respectively

For each sea-state determine stress response spectra from combined first and second order effects

Apply statistics (e.g. Single moment method or Rayleigh distribution) to obtain damage due to each sea-state

Multiply damage by probability of occurrence and sum for all sea-states

Repeat for other loading directions and sum for total damage

### Method 3

With method 3 the first and second order fatigue damages are calculated separately then summed together to obtain the total fatigue damage. The procedure for method 2 is outlined in the steps below:

#### First Order Motions

Discretise wave scatter diagram into linearisation windows, as in Figure 3

Select representative sea-state from each linearisation window, which shall yield equal or greater damage than the original seastates

Use selected sea-states in non-linear time-domain analysis, with associated mean offset

Combine tension and bending to obtain total stress

Fourier analysis of total stress time-traces to get stress range transfer functions around circumference for each window, as in Figure 4

Apply statistics (e.g. Rayleigh distribution) to obtain damage due to each sea-state in window

Multiply damage by probability of occurrence and sum for all sea-states in window

Repeat for each window

Repeat for other loading directions and sum for total damage

#### Second Order Motions

Discretise the scatter diagram into windows or analyse every sea-state in the scatter diagram, depending on the required level of detail

Conduct quasi-static riser analysis using second order FPS motions

Determine RMS stress response in each condition

Apply statistics (e.g. Rayleigh distribution) to obtain damage due to each sea-state

Multiply damage by probability of occurrence and sum damage for all sea-states

Repeat for required number of loading directions and sum for total damage.

Combining Fatigue Damage from First and Second Order Motions

Sum first and second order damages at each point on riser pipe circumference and along the riser length

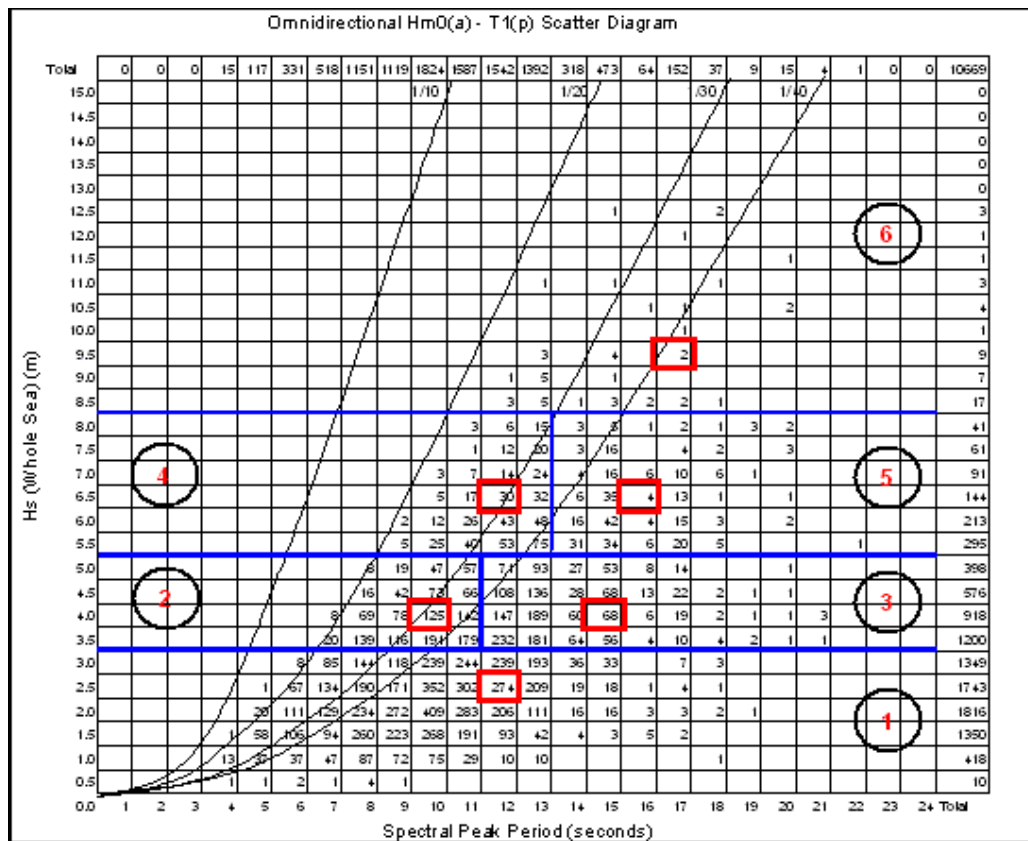


Figure 2 – Example Windowing and Sea-State Selection of Long-Term Scatter Diagram

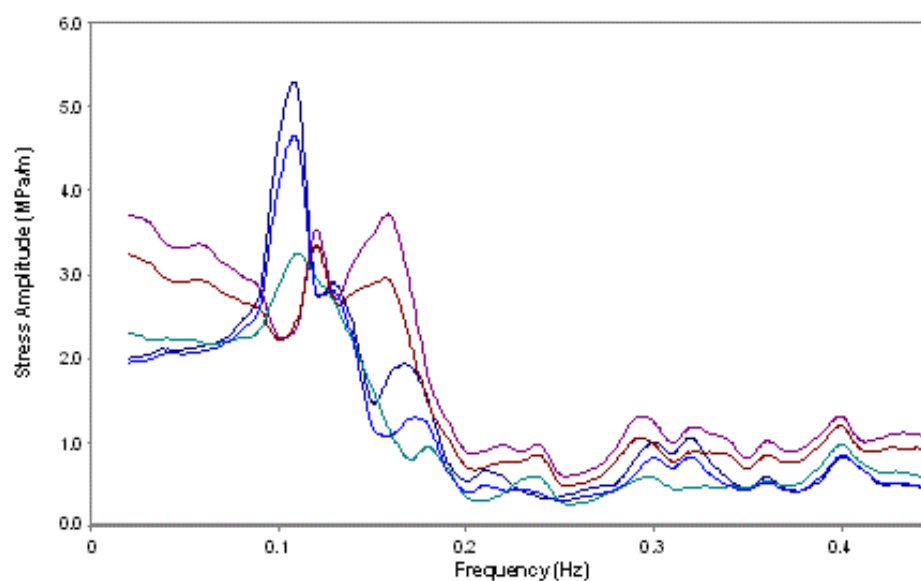


Figure 3 – Example Stress RAO at Each of Eight Points Around the Circumference

## Single Moment Method of Lutes and Larsen

The fatigue damage expression given by Lutes and Larsen involves one moment of the spectral density function and can be written as follows [4] [5]:

$$\text{fatigue damage} \quad \bar{D} = \frac{T}{2\pi K} \cdot (2\sqrt{2})^m \cdot \Gamma\left(\frac{m}{2} + 1\right) \cdot (\lambda_{2/m})^{m/2} \quad (1)$$

$$\text{cycles to failure} \quad N = K \cdot S^{-m} \quad (2)$$

$$\text{single moment} \quad \lambda_{2/m} = \int_0^{\infty} \omega^{2/m} \cdot G(\omega) \cdot d\omega \quad (3)$$

where

|             |   |                                                  |
|-------------|---|--------------------------------------------------|
| T           | = | duration                                         |
| K, m        | = | parameters of the S-N curve, which is defined by |
| S           | = | stress-range                                     |
| $G(\omega)$ | = | spectral density function of stress-range        |
| $\omega$    | = | frequency in rad/sec                             |

This method requires no more effort than the Rayleigh method, but the results are generally more accurate.

## References

- [1] "Probabilistic analysis of fatigue due to Gaussian load processes", Jiao, G., and Moan, T., Probabilistic Engineering Mechanics, Vol.5 No.2, 1990.
- [2] "Fatigue Under Wide Band Random Stresses", Wirsching, P., and Light, M.C., Journal of the Structural Division, ASCE, Vol.106, No.ST7, pp.1593-1607, July 1980.
- [3] "Fatigue Damage Prediction for Stationary Wideband Stresses", Ortiz, K., and Chen, N.K., 5th Int. Conf. on Application of Statistics and Probability in Soil and Structural Engng., 1987.
- [4] "Improved Spectral Method for Variable Amplitude Fatigue Prediction", Lutes, L.D., and Larsen, C.E., J. Struct. Engng., Vol. 116, No. 4, pp.1149-1164, April 1990.
- [5] "Predicting the fatigue life of offshore structures by the single-moment spectral method", Larsen, C.E., and Lutes, L.D., Probabilistic Engineering Mechanics, Vol. 6, No. 2, pp.96-108, 1991.
- [6] "Fatigue Damage due to Wide Band Random Processes", Memorandum from B. Stahl to P. Beynet (BP), Houston, Texas, 20th July 2000.

## Appendix 12 Spreading of VIV Fatigue Damage in the TDZ

### Introduction

VIV fatigue analysis is initially performed with the FPS in the neutral position. Apart from VIV, no other dynamic forces or motions are accounted for in this initial analysis. Under these assumptions it is found that the predicted fatigue damage in the TDZ peaks sharply at anti-nodes of the calculated mode shapes, where curvature and bending stress peak. This results in large variations in the predicted fatigue damage between anti-nodes, the extent of this effect depends on which modes, and how many, are mobilised.

In reality, riser system properties and boundary conditions vary continuously. The TDP shifts under the influences of FPS motion and direct hydrodynamic loading on the riser, and the riser mass changes for various reasons over time. This means that mode-shapes are continuously changing, and so are the locations of modal anti-nodes on the riser. This effect tends to even out peaks and troughs in the calculated damage curve. The true fatigue damage in this region is thus less than that predicted by the 'stationary' riser system assumed in the initial VIV analysis.

### Effects of VIV Fatigue Damage Spreading

The factors that cause the TDP to move and hence VIV fatigue damage spreading at the TDP are numerous, and include both short-term and long-term effects over the riser service life. Factors to consider when spreading VIV fatigue damage include:

- First order wave induced FPS motions causing the TDP to move
- Mean and second order FPS motions due to wind, wave and current loading
- FPS draught and tidal variations
- Long-term riser contents density – variations as a reservoir becomes depleted and the composition of both the produced and exported fluids change

Secondary effects that may be considered in damage spreading include:

- Variation of current force applied directly to the riser
- Offsets of FPS with direct well access to make way for drilling may be applied over a substantial period
- Additional risers phased in at a later stage imposing incremental offsets
- Short-term riser fluid density variations, such as slugs
- Riser mass variation from long-term effects; e.g. corrosion and water absorption in auxiliary buoyancy
- Riser/soil interaction – trenching or soil suction in the TDZ that could effect the TDP position

### Methods for Spreading VIV Fatigue Damage

Two methods for spreading VIV fatigue damage at the TDP are given below:

Method 1: Analyse the riser at different offsets, then factor and combine the VIV fatigue damage

Method 2: Analyse the riser in the neutral position and spread the damage using statistics

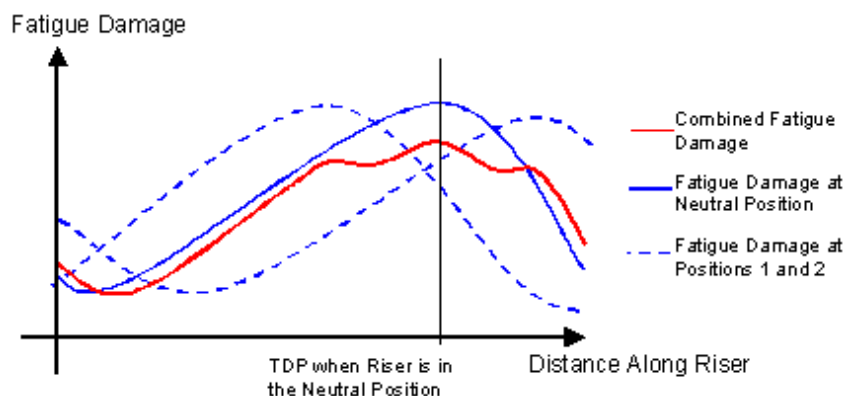
### Method 1

With method 1 the VIV analysis is conducted first with the FPS in the neutral position and with the FPS located typically at offsets corresponding to near and far RMS slow drift.

The VIV fatigue damage is factored by the probability of occurrence (table 1) of the riser being in these positions before it is summed together (fig. 1):

| Position         | Factor |
|------------------|--------|
| Neutral Position | 0.50   |
| RMS Offset       | 0.25   |

**Table 1**



**Figure 1 - Typical VIV Fatigue Damage Factors**

### Method 2

With method 2, the VIV analysis is run and the VIV fatigue damage is spread over a characteristic length,  $L_s$ .

Contributing characteristic lengths,  $L_{s,i}$ , may be determined for the different causes TDP movement (see section 2) and summed together using equation (1)

$$L_s^2 = \sum L_{s,i}^2 \quad (1)$$

It is possible that only a single value of  $L_s$  is required, applicable across all initial VIV fatigue analyses.

If currents from different directions contribute significantly to fatigue damage it may be necessary to use more than one value of  $L_s$  – each corresponding to a current direction and associated probability of occurrence.

Typically characteristic lengths are estimated from the RMS displacement range of TDP movement.

Typical characteristic lengths for some of the effects listed above, such as second order motions, are given in Table 2 for VIV analysis using transverse currents and Table 3 for VIV analysis using in-plane currents.

| Parameter                     | Characteristic Lengths (m) |
|-------------------------------|----------------------------|
| Second Order Motion           | $L_{S1,1}$                 |
| Transverse Currents           | $L_{S1,2}$                 |
| Tidal variation               | $L_{S1,3}$                 |
| Overall Characteristic Length | $L_{S1}$                   |

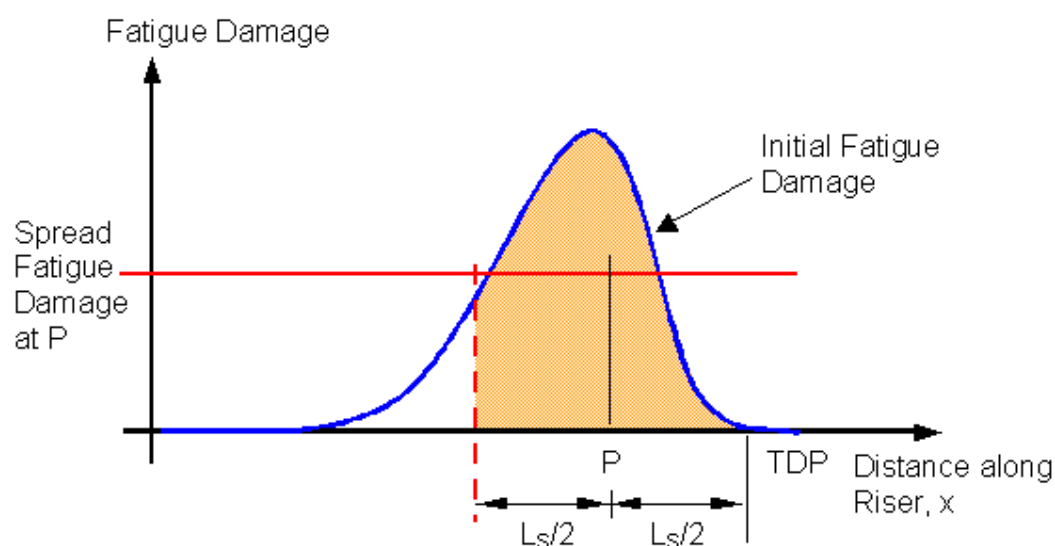
**Table 2 – Transverse Current Case**

| Parameter                     | Characteristic Lengths (m) |
|-------------------------------|----------------------------|
| Second Order Motion           | $L_{S2,1}$                 |
| In-plane Currents             | $L_{S2,2}$                 |
| Tidal variation               | $L_{S2,3}$                 |
| Overall Characteristic Length | $L_{S2}$                   |

**Table 3 – In-Plane Current Case**

Calculate the fatigue damage from the initial VIV analysis, then for each point P in the vicinity of the TDP, average the initial fatigue damage over a distance  $L_S$ , centred on P, Figure 2.

Repeat this process for different points along the riser.



$$\text{Spread Fatigue Damage at P} = \text{Shaded Area} / L_S$$

**Figure 2 – VIV Fatigue Damage Spread Using Method 2**

## Appendix 13 Vortex Induced Vibrations

### Frequency Ratio

For vortex induced vibrations, the in-line oscillation frequency is double the cross-flow oscillation frequency, that is:

$$f_z = 2f_y \quad (1)$$

### Modal Number Ratio

#### Beam Behaviour

The natural frequencies of transverse vibration of uniform pinned-pinned beams under uniform axial load are given by:

$$f_n = \frac{1}{2\pi} \left( \frac{n\pi}{L} \right)^2 \left( \frac{EI}{m} \right)^{\frac{1}{2}} \left[ 1 + \left( \frac{L}{n\pi} \right)^2 \frac{T}{EI} \right]^{\frac{1}{2}} \quad (2)$$

where:

- $n$  : mode number,
- $L$  : beam length,
- $EI$  : flexural stiffness,
- $m$  : mass per unit length, including content and added mass,
- $T$  : axial force (positive if the load is tensile).

For high mode numbers, when  $n \gg (L/\pi) \sqrt{T/EI}$ , relationship (2) reduces to the expression for natural frequencies of transverse vibration of uniform pinned-pinned beams under no axial load, i.e.:

$$f_n \cong \frac{1}{2\pi} \left( \frac{n\pi}{L} \right)^2 \left( \frac{EI}{m} \right)^{\frac{1}{2}} \quad (3) \quad \text{which can be rewritten as} \quad f_n \cong n^2 f_1 \quad (4)$$

$$\text{So that the ratio of two different natural frequencies can be expressed as } \frac{f_n}{f_m} \cong \left( \frac{n}{m} \right)^2 \quad (5)$$

$$\text{As VIV is considered, eq. (1) applies and eq. (5) results in: } n_z \cong \text{nearest integer}(\sqrt{2} n_y) \quad (6)$$

#### String Behaviour

$$\text{For straight cables } (EI \cong 0), \text{ relationship (2) reduces to: } f_n = \frac{n}{2L} \left( \frac{T}{m} \right)^{\frac{1}{2}} \quad (7)$$

$$\text{which can be rewritten as: } f_n = n f_1 \quad (8)$$

$$\text{Hence, the ratio of two different natural frequencies can be expressed as: } \frac{f_n}{f_m} = \frac{n}{m} \quad (9)$$

$$\text{As VIV is considered, eq. (1) applies and eq. (9) results in: } n_z = 2n_y \quad (10)$$

## Stress Ratio

A straight uniform section of pipe under constant tension is considered.

It is assumed that the vortex induced vibrations of the structure in the cross-flow and in-line planes can be described by the following expressions, respectively:

$$y(x, t) = A_y \sin\left(\frac{n_y \pi x}{L}\right) \sin(2\pi f_y t + \phi_y) \quad (11) \quad z(x, t) = A_z \sin\left(\frac{n_z \pi x}{L}\right) \sin(2\pi f_z t + \phi_z) \quad (12)$$

where:

|                                    |                                 |
|------------------------------------|---------------------------------|
| $y$ : cross-flow displacement,     | $A_z$ : in-line amplitude,      |
| $A_y$ : cross-flow amplitude,      | $n_z$ : in-line mode number,    |
| $n_y$ : cross-flow mode number,    | $f_z$ : in-line frequency,      |
| $f_y$ : cross-flow frequency,      | $\phi_z$ : in-line phase angle, |
| $\phi_y$ : cross-flow phase angle, | $L$ : pipe length,              |
| $z$ : in-line displacement,        | $x$ : axial co-ordinate,        |
|                                    | $t$ : time.                     |

By double differentiating the above relationships with respect to the axial co-ordinate, the following expressions for maximum curvature in the two planes are obtained:

$$y''_{max} = A_y \left(\frac{n_y \pi}{L}\right)^2 \quad (13) \quad z''_{max} = A_z \left(\frac{n_z \pi}{L}\right)^2 \quad (14)$$

This results in the following maximum stresses in the cross-flow and in-line planes, respectively:

$$\sigma_{y, max} = \frac{1}{2} E D y''_{max} = \frac{1}{2} E D A_y \left(\frac{n_y \pi}{L}\right)^2 \quad (15) \quad \sigma_{z, max} = \frac{1}{2} E D z''_{max} = \frac{1}{2} E D A_z \left(\frac{n_z \pi}{L}\right)^2 \quad (16)$$

where:  $E$  : Young's modulus,  
 $D$  : pipe outer structural diameter.

The ratio of maximum stress in the in-line direction to maximum stress in the cross-flow direction results:

$$\frac{\sigma_{z, max}}{\sigma_{y, max}} = \left(\frac{n_z}{n_y}\right)^2 \frac{A_z}{A_y} \quad (17)$$

## Beam Behaviour

For beam behaviour and high mode numbers, relationship (A6) applies and relationship (17) reduces to:

$$\frac{\sigma_{z, max}}{\sigma_{y, max}} \cong 2 \frac{A_z}{A_y} \quad (18)$$

## String Behaviour

For string behaviour, relationship (9) applies and relationship (17) reduces to:

$$\frac{\sigma_{z, max}}{\sigma_{y, max}} = 4 \frac{A_z}{A_y} \quad (19)$$

## Damage Ratio

The fatigue curve for the pipe material is assumed to be given by:  $N(\Delta\sigma) = C (\Delta\sigma)^{-b}$  (20)

where:  $N$  : number of cycles to failure at  $\Delta\sigma$        $\Delta\sigma$ : stress range ( $= 2\sigma_{max}$ )  
 $C$  : fatigue curve constant       $b$  : fatigue curve exponent

The maximum damage rates per year in the cross-flow and in-line directions are respectively given by:

$$D_y = \frac{n(\Delta\sigma_y)}{N(\Delta\sigma_y)} = \frac{T}{C} f_y (\Delta\sigma_y)^b = \frac{T}{C} f_y (2\sigma_{y,max})^b \quad (21) \quad D_z = \frac{n(\Delta\sigma_z)}{N(\Delta\sigma_z)} = \frac{T}{C} f_z (\Delta\sigma_z)^b = \frac{T}{C} f_z (2\sigma_{z,max})^b \quad (22)$$

where:  $n$  : number of cycles,       $N$  : number of cycles to failure,  
 $\Delta\sigma$ : stress range,       $T$  : one year expressed in seconds.

The ratio of maximum damage rate per year in the in-line direction to the cross-flow direction results:

$$\frac{D_z}{D_y} = \frac{f_z \left( \frac{\sigma_{z,max}}{\sigma_{y,max}} \right)^b}{f_y \left( \frac{\sigma_{z,max}}{\sigma_{y,max}} \right)^b} = \frac{f_z}{f_y} \left[ \left( \frac{n_z}{n_y} \right)^2 \frac{A_z}{A_y} \right]^b \quad (23)$$

## Beam Behaviour

For beam behaviour and high mode numbers, relationships (1) and (6) apply, so relationship (23) reduces to:

$$\frac{D_z}{D_y} \equiv 2 \left[ 2 \frac{A_z}{A_y} \right]^b \quad (24)$$

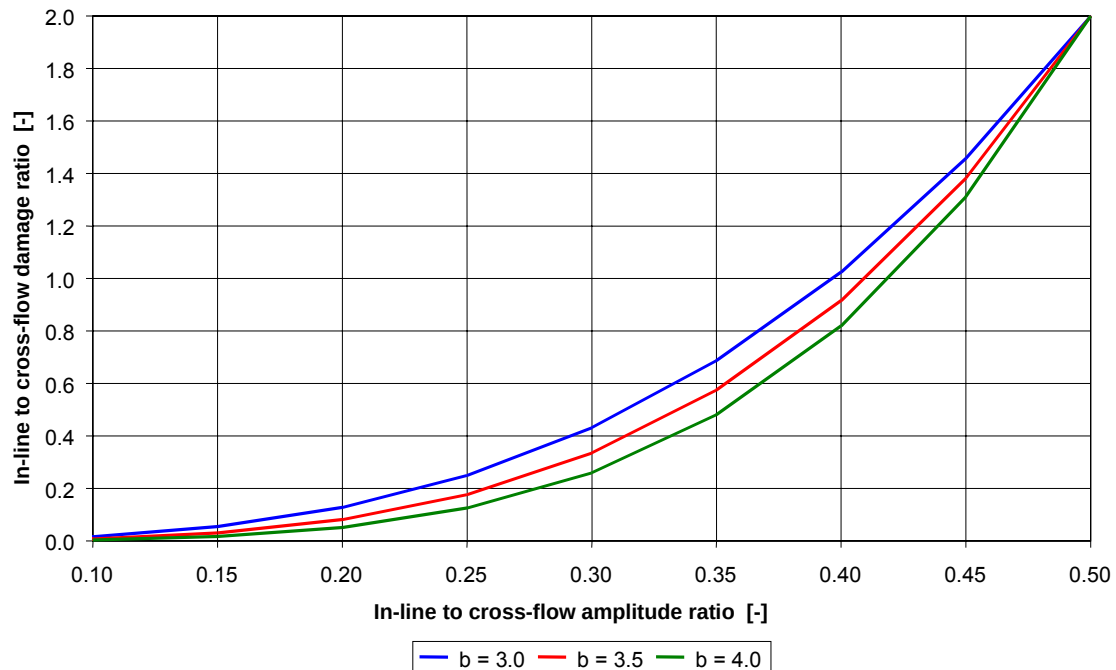
The ratio of maximum damage rate per year vs. the ratio of in-line to cross-flow amplitude is depicted in Figure 1, for different fatigue curve exponents.

## String Behaviour

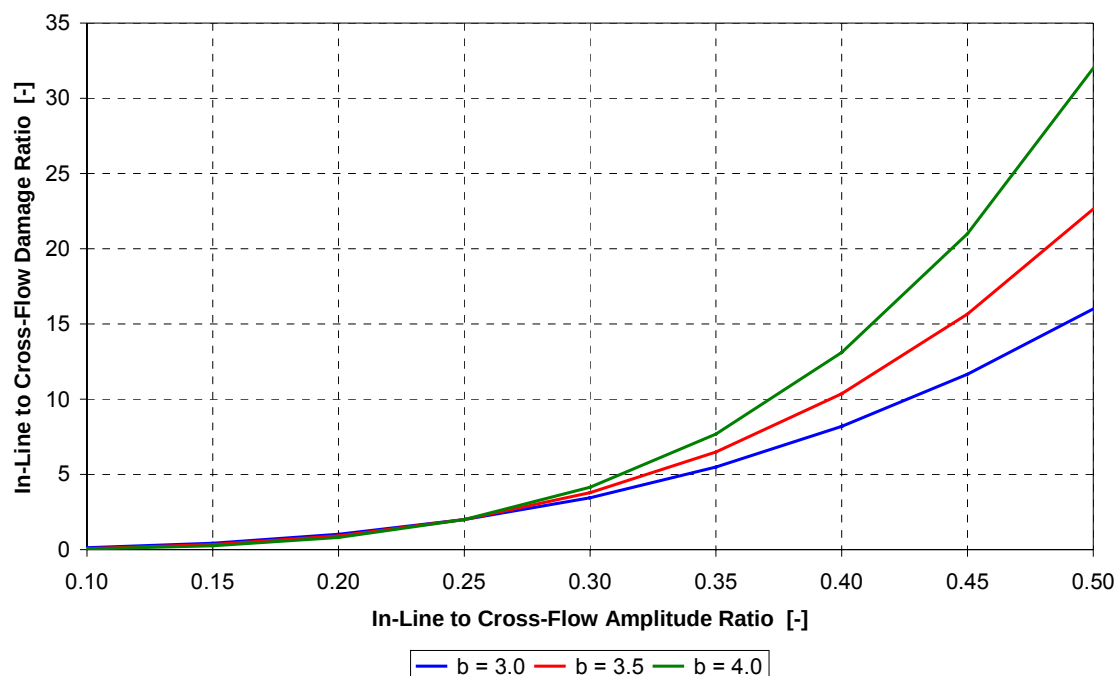
For string behaviour, relationships (1) and (9) apply, so relationship (23) reduces to:

$$\frac{D_z}{D_y} = 2 \left[ 4 \frac{A_z}{A_y} \right]^b \quad (A6.25)$$

The ratio of maximum damage rate per year Vs the ratio of in-line to cross-flow amplitude is depicted in Figure 2, for different fatigue curve exponents.



**Figure 1 - Pipe section with beam behaviour: in-line to cross-flow damage ratio Vs in-line to cross-flow amplitude ratio for different fatigue curve exponents**



**Figure 2 - Pipe Section with String Behaviour: In-Line to Cross-Flow Damage Ratio Vs. In-Line to Cross-Flow Amplitude Ratio for Different Fatigue Curve Exponents**

## Appendix 14 Static sizing

### Geometry

Initial wall thickness estimates are made using assumed riser loads, obtained from static sizing.

### Static sizing

Catenary equations may be used to derive an initial SCR geometry and loading.

$$y = \frac{H}{mg} \left[ \cosh\left(\frac{mgx}{H}\right) - 1 \right]$$

$$S = \frac{H}{mg} \sinh\left(\frac{mgx}{H}\right)$$

$$T = H + mgy$$

where

- y height of a point on the riser above the seabed
- H horizontal tension at the TDP
- m submerged mass per unit length
- g acceleration due to gravity
- x horizontal distance of a point on the riser from the TDP
- S length of the riser between the TDP and a point
- T tension at a point on the riser

### Initial Riser Geometry

From the above equations relationships for the distance between the FPS and the TDP and the length of the riser can be calculated from the top angle and the height of the riser attachment point above the seabed.

$$x_{TDP} = y_A \frac{(\cos \alpha_{TOP}) \times \operatorname{arcsinh}(\tan \alpha_{TOP})}{(1 - \cos \alpha_{TOP})}$$

$$S_R = y_A \frac{(\cos \alpha_{TOP}) \times (\tan \alpha_{TOP})}{(1 - \cos \alpha_{TOP})}$$

where

- $x_{TDP}$  horizontal distance between the FPS and the TDP
- $y_A$  height of the riser attachment point above the seabed
- $\alpha_{TOP}$  angle between the horizontal axis and the riser at the riser attachment point in radians
- $S_R$  length of the riser pipe between the FPS and the TDP

### Initial Riser Loads

From the initial geometry and an estimation of the submerged pipe weight and the second moment of area, the tension at the TDP, the top tension and the bending moment at the TDP can be estimated using the equations below:

$$H = \frac{mgS_R}{\tan \alpha_{TOP}}$$

$$T_{TOP} = \frac{H}{\cos \alpha_{TOP}}$$

$$M_{TDP} = \frac{-mg}{H} EI$$

where

- g acceleration due to gravity
- $T_{TOP}$  top tension
- $M_{TDP}$  bending moment at the TDP